sAND90-0224
Unlimited Release
December 1991

UC-126

Strategic Petroleum Reserve (SPR)
Additional Geologic Site Characterization Studies
West Hackberry Salt Dome, Louisiana

Thomas R. Magorian
Amherst, New York

James T. Neal
Sandia National Laboratories
Albuquerque, New Mexico

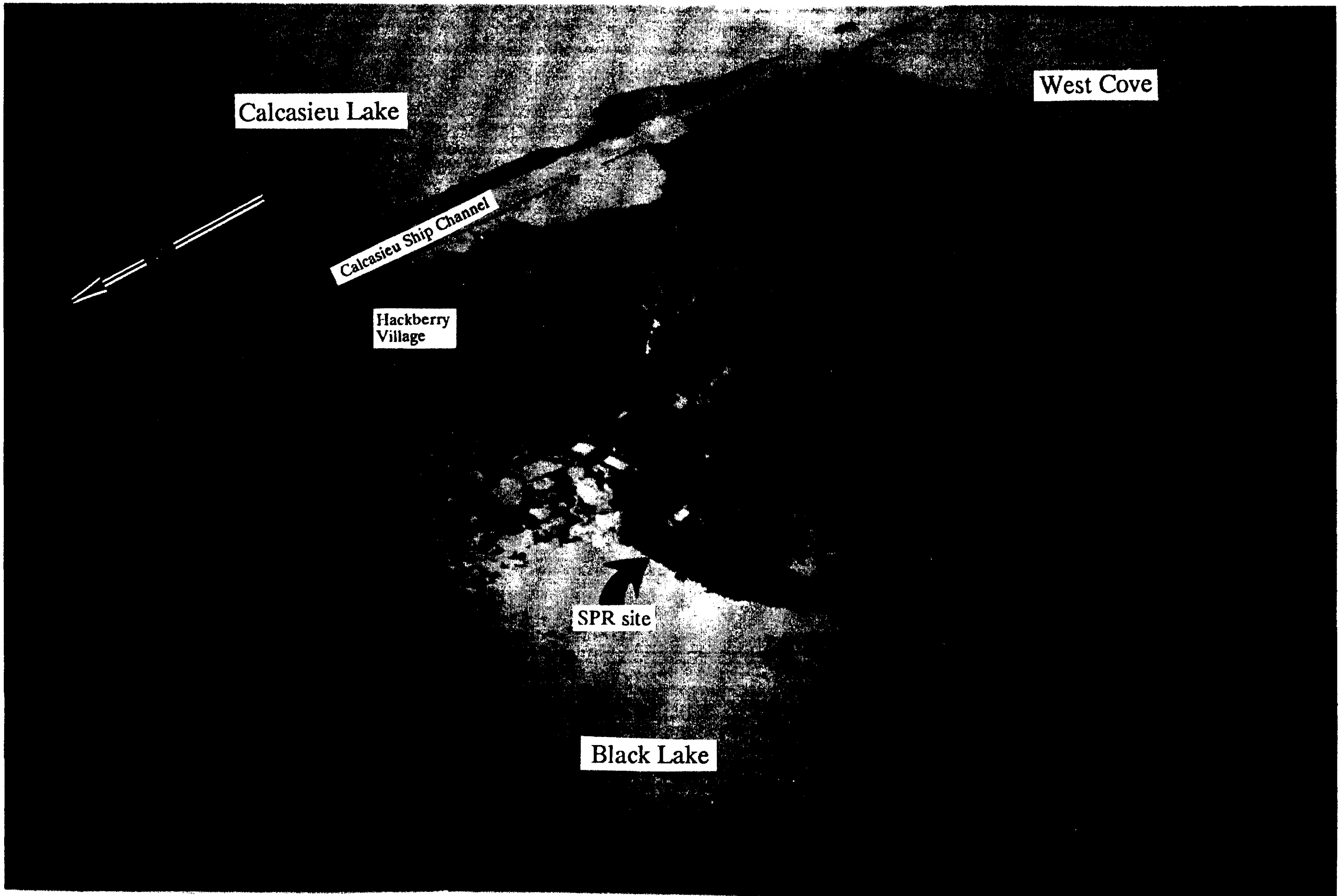
Stephen Perkins, Qiang J. Xiao, Kathleen 0. Byrne
Acres International Corporation
Amherst, New York

Prepared by Sandia National Laboratories
Albuquerque, NM 87185 and Livermore, CA 94550
for the U. S. DOE under Contract DE-AC04-76DP00789

ABSTRACT

This report is a revision and update of the original geologic site characterization report that was published in 1980. Many of the topics addressed in the earlier report were predictive in nature and it is now possible to reexamine them some 12 years later, using the data from 17 new caverns and more than ten years of SPR storage experience.

Revised maps of the salt configuration show an overhang and faults on the north side of the dome, defining more clearly the edge relationships with respect to the SPR caverns. Caprock faults may locally influence the pattern of subsidence, which is occurring primarily as a result of cavern creep closure. The greater subsidence rate occurring at West Hackberry will likely require mitigative action within a few years. Seismicity of low intensity recurs infrequently at West Hackberry, but a small earthquake in 1983 caused dish rattling in the immediate vicinity.



Frontispiece: High-altitude view of West Hackberry SPR site, showing the ~20 ft "island" over the dome surrounded by coastal marshlands. Gulf of Mexico is 5 mi from top of photo, due south of West Cove.

TABLE OF CONTENTS

Strategic Petroleum Reserve (SPR)
Additional Geologic Site Characterization Studies
West Hackberry Salt Dome, Louisiana

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION AND PURPOSE

The initial geologic site characterization report [Ref. l] was completed in 1980, when only the five caverns that were acquired from the Olin Corporation (#s 6,7,8,9, and 11) existed. Since that time 18 cavern wells were drilled and 17 new caverns were leached and are now some 90% filled with crude oil, toward the currently authorized site capacity of 219 million barrels (MMB). The construction of the new caverns has significantly enhanced our confidence in understanding the salt dome features.

In addition to information that has become available during more than 10 years of SPR operation, new data are also available from numerous commercial wells adjacent to the site.

This report is a revision and update of the earlier site characterization report, placing the geologic understanding in better perspective. Several aspects are given special'attention in the report: salt contours and structural interpretations as they relate to cavern integrity; subsidence history over SPR caverns; and potential flooding during future operations. In numerous cases, the original maps are re-interpreted in light of the new information, and with reference to current (1991) concepts of Gulf Coast geology.

New or Revised Information

The 18 new cavern wells provided detailed information on the character of the salt mass and also the salt contours on top of the dome. A new salt map is presented, along with new interpretations of the structural geological configuration. These have been aided by oil company interpretations and data, especially on the north side adjacent to Black Lake.

Configurations of the 22 caverns are discussed, along with the ten-year operating history at the site. Few, if any, problems exist although Cavern 111 has behaved in an atypical manner. The 3-dimensional computer model shows that Cavern 111 is approximately 200 ft further from the edge of the salt than previously estimated. However, a fault and shear zone have been found in its vicinity.

Subsidence occurring over the cavern field has been resurveyed annually for some eight years at more than eighty survey points, and sufficient data exist to make definitive judgments on future direction. The data show that West Hackberry is subsiding at a greater rate than the other SPR sites and that the areas on the site with low elevation will eventually require protection from permanent inundation. The adjacent coastal marshlands are also subsiding and some 35 sq mi/yr of south Louisiana is becoming open water and part of the Gulf of Mexico. Present conditions and future trends suggest that the higher portions of the West Hackberry site are effectively an island in the marsh (see frontispiece), and that eventually it will be a small island in open water with direct connections to the Gulf.

Hurricane surge heights have been revised to a higher value than previously indicated; current 100 yr flood stage heights are about 10 ft above mean sea level (amsl) at the site. The eye of Hurricane Audrey in 1957 passed about 12 mi west of the site and produced high water marks of 10 ft above mean sea level at that location.

National seismic zonation maps have been refined in the past ten years, but the Gulf Coast interpretation is little changed, the area being essentially aseismic. Nonetheless, new data and a small earthquake (1983) near the site are discussed.

GEOUGIC ASPECTS

The geologic discussion presented in Appendix A complements that given in the earlier report [Ref. l] and is not intended to duplicate it. The geologic information base is needed to help maintain the integrity of the oil storage caverns and includes the extent and character of the salt dome in its regional setting. The salt mass containing the oil is in turn held and stabilized by the regional sediments into which the salt dome is intruded. The low-permeability muds, particularly those at geopressure forming the shale sheath, form additional protection for any oil stored in the dome [Ref. 21. Figures 1 and 2 are structural contour maps showing depth to Anahuac and Hackberry shale units, respectively. Figure 2 also shows the location of cross-sections used in subsequent figures. Table 1 explains the abbreviated stratigraphic units shown on the sections.

Hydrology

Fresh water is found on the island in the upper glacial-equivalent sands of the Chicot aquifer. The Wisconsin is freshest and most potable, although the Illinoian is also suitable for industrial use. The lower Wisconsin or Alton is referred to as the 200 ft aquifer.

The water in the caprock may contain quantities of hydrogen sulfide. At the base it is saturated brine in equilibrium with the salt that it is dissolving. Deeper waters in hydrocarbon-bearing sands around the dome vary from fully saturated brines in the more massive Miocene sands mineralized close to the salt, to anomalously-fresh carbonate-saturated brines rich in boron, vanadium and other ocean-floor concentrates in isolated sands in contact with geopressured shales.

The DOE injection well field is located on the opposite (south) side of the dome from the oil storage caverns. Directionally drilled from a central pad on the steep southeast flank of the dome, all the wells were completed in the RL zone at the top of the lower Miocene (see Table 1). This well-sorted marine bar sand exhibits good permeability at the top and dips 30 degrees south-southeast. All of the wells took brine at relatively good rates initially.

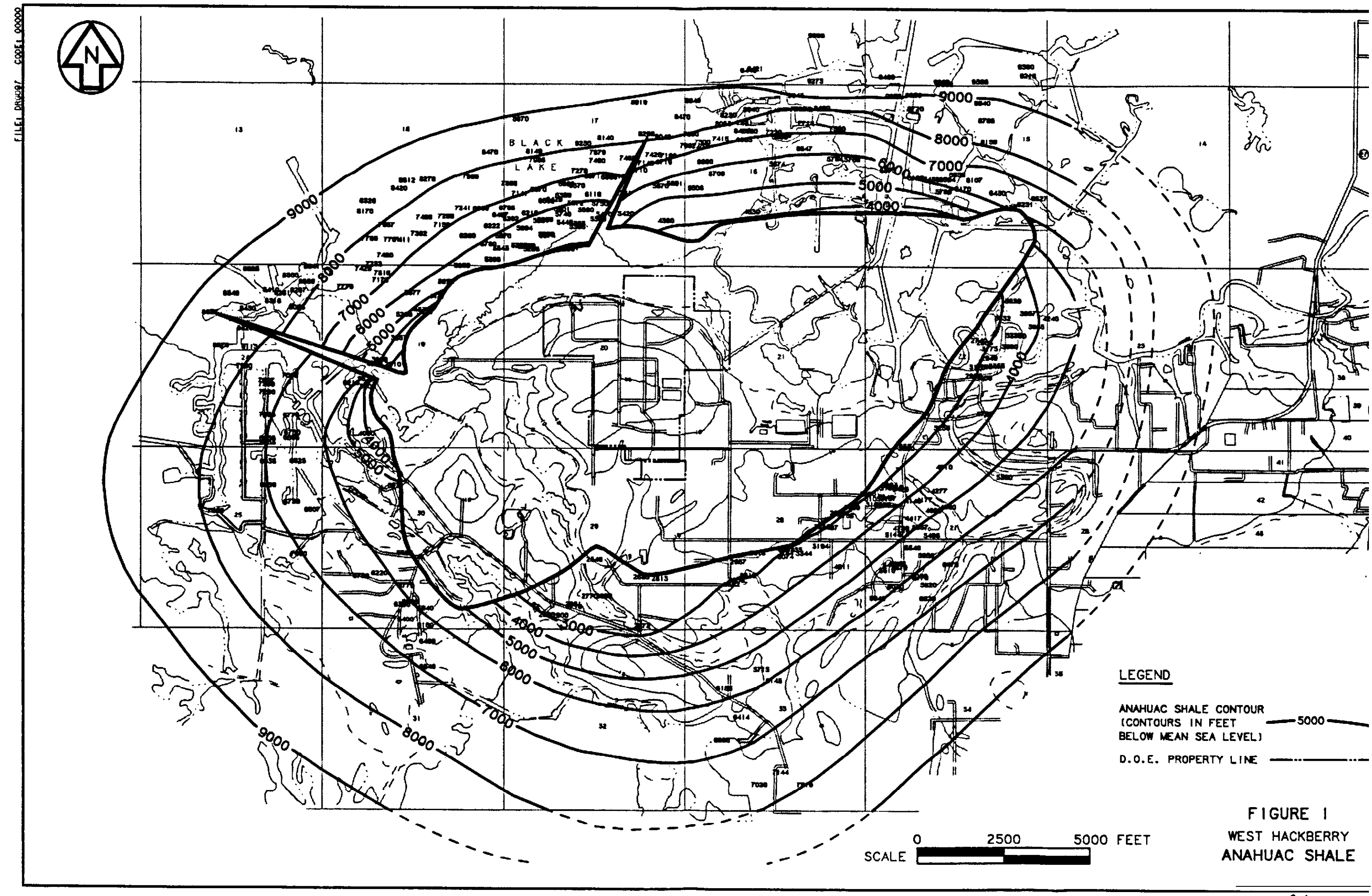


FIGURE 1
WEST HACKBERRY
ANAHUAC SHALE

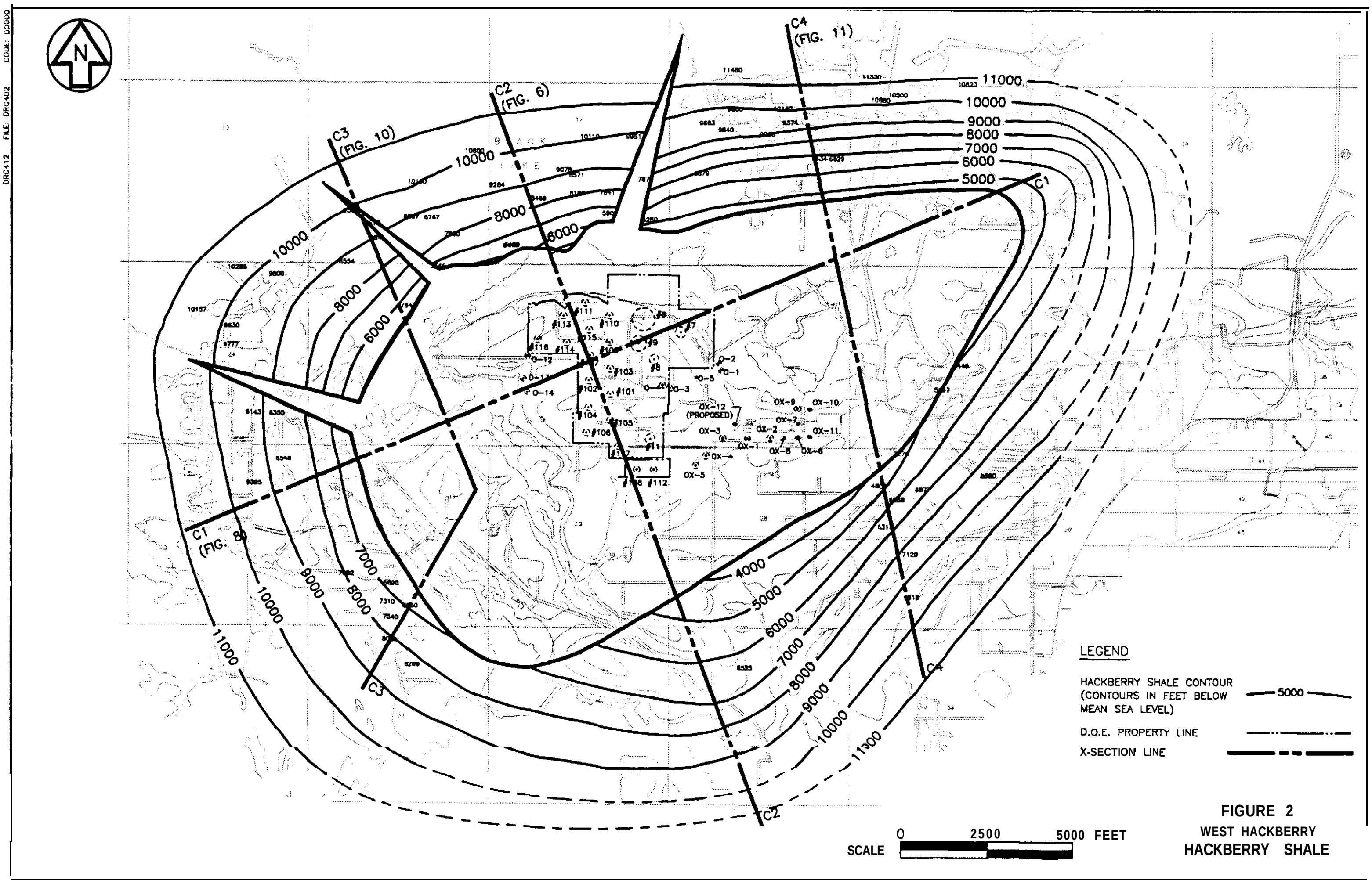


FIGURE 2
WEST HACKBERRY
HACKBERRY SHALE

With the completion of the brineline to the Gulf in 1980, these disposal wells have been on standby most of the time. When the brineline has been shut down for repairs, the wells have required extensive acidization, the screens have been eaten away and the holes have filled with sand. Expensive workovers have not cured the problems, resulting in injection costs per barrel that are greater than those experienced at other SPR sites.

These existing wells can potentially be reconditioned cost-effectively using industry recompletion practices that have been developed in the intervening 15 years since these wells were installed. At this location the upper Miocene sands are thin and relatively impermeable, the Pliocene silty, and the upper Pleistocene is fresh-water-bearing, so the best-available recompletion zone is in the basal Pleistocene Lafayette gravel and the immediately overlying Nebraskan gravel. These units are point-bar river gravels which have the basal permeability required for successful brine injection.

Figure 3 shows a fresh upper Illinoian gravel at a depth of 830 ft in contact with a saline lower gravel, above a Kansan unit at 1520 ft that is too thin to use for injection, and an attractive basal gravel at 1670 ft.

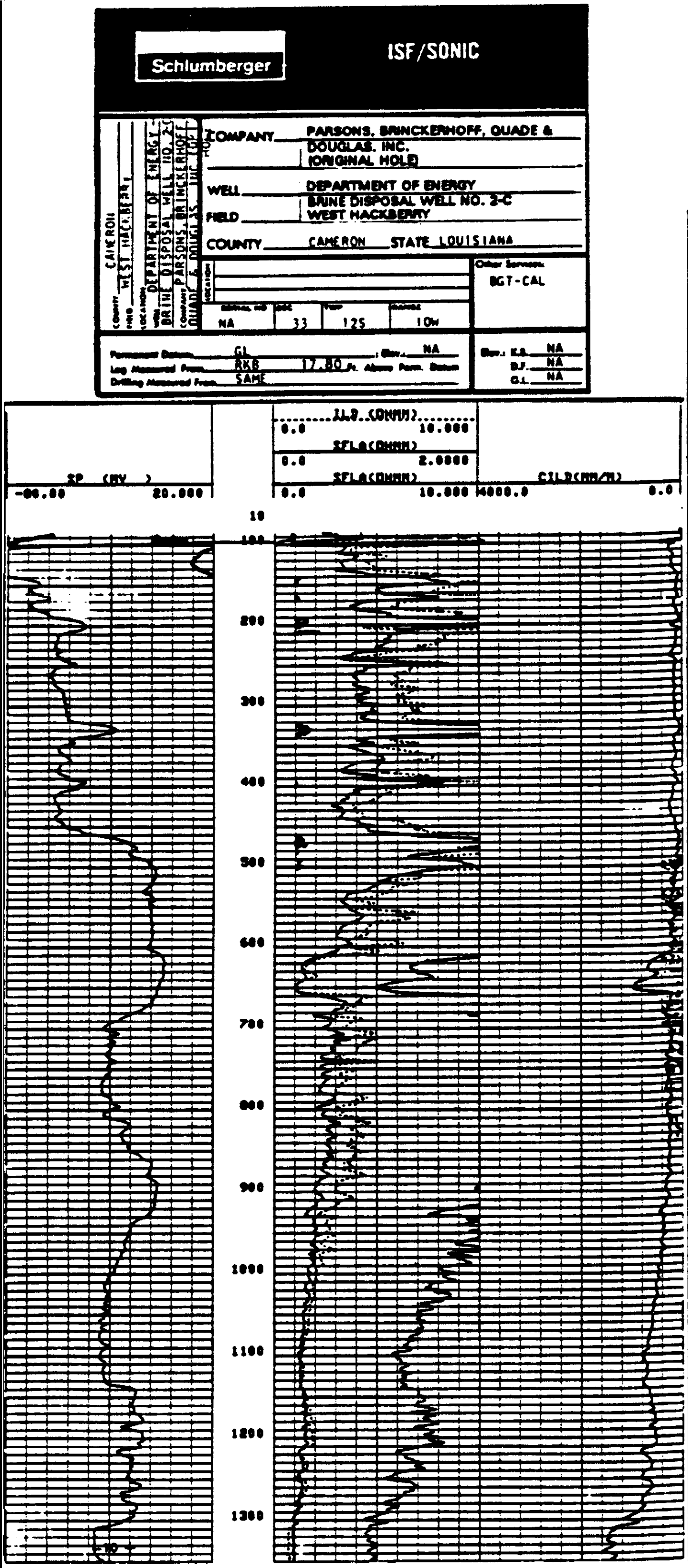
The industry technique of recompleting a well by simply perforating the pipe above the screen has become standard, eliminating the many problems encountered in successfully maintaining screened completions. With relatively large-diameter pipe in these wells (9 5/B" final casing; 7" injection string), sustained injection rates of 30,000 barrels per day should be achievable.

By leaving the rest of the hole open, the inevitable sand fill which occurs during shutdowns needs be cleaned out only at long intervals. By recompleting in relatively-clean river gravels, the amount of sand fill in the wells can be minimized at a rate far below that of the original "gravel packs," which are actually 20-40 mesh Ottawa sand occurring behind the screens in the DOE wells, and which is ejected when these screens are destroyed during acidization.

The permeability of the injection gravels will decline with any particulates injected with the brine. Thus the required injection rates cannot be maintained without surface facilities to settle and filter the brine; alum in the brine pond in combination with cyclones and polishing filters are more effective than the original sand filters eventually installed at SPR sites. Additional data on these injection zones can be found in Reference 3.

Caprock

The caprock top is a massive carbonate, a correlative unit that can be traced all the way across the dome at approximately 1600 ft below sea level (Figure 4). This unit is a dense but cavernous lime marker with a distinct resistivity signature on electric logs.



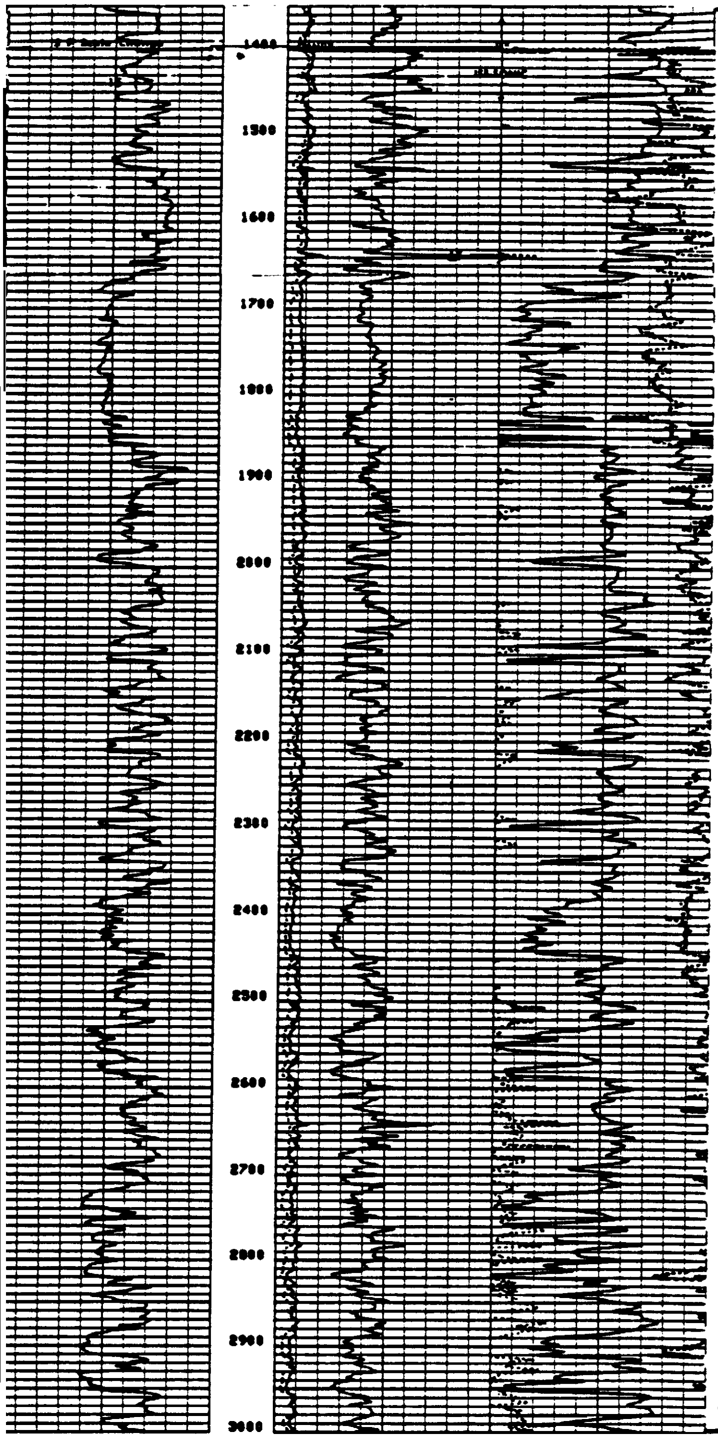
WEST HACKBERRY DOE BRINE DISPOSAL WELL NO. 2-C

Stratigraphic Symbol	Lithology	Permeability (Darcies)	Salinity
	25' Recent MUCK & CLAY		
	100' Wisconsin SAND & GRAVEL Base of fresh water		100 ppm
	530' Sangamon CLAY		
	660' Illinoian SAND & GRAVEL	4	5000 – 6000 ppm
	1130' CLAY		
	1310' Kansan SAND & GRAVEL	2	27 %

Figure 3

SHEET 1 OF 2

WEST HACKBERRY
DOE BRINE DISPOSAL WELL
NO. 2-C



Stratigraphic Symbol	Lithology	Permeability (Darcies)	Salinity
	1350' CLAY		
	1660' Nebraskan/Lafayette SAND & GRAVEL	5	30 %
	1860' Pliocene – SILT with thin SAND layers		

Figure 3 (cont.)

SHEET 2 OF 2

TABLEl- WEXT **HACKBERRY STRATIGRAPHIC CORRELATION CHART**

	Unit	Symbol	Lithology
	Recent: ***Beaumont clay***		peat, muck 6 mud
QUATERNARY	Pleistocene		
	Wisconsin		
	Alton/Peorian: ***Prairie Fm.***	a	sand and gravel
	Sangamon: ***Montgomery Fm.***	S	mud
	Illinoian	i	sand and gravel
	Yarmouthian: ***Bentley*** Fm.	(P)	mud
	Kansan	ka/ks	sand and gravel
	Aftonian: ***Williana Fm.***		mud
	Nebraskan	ne	sand and gravel
	Lafayette		gravel
TERTIARY	Pliocene	PL	silt, mud, and sand
	Miocene	MI	mud 6 sand
	Upper		
	Bigenerina fforidana	**A**	sand and gravel
			mud
		B	sand and gravel
			mud
	Textularia	L	marine sand
	Bigenerina nodosaria	***2***	deltaic sand
			mud
	Textularia stapperi	W	deltaic sand
			mud
	Middle		
	Bigenerina humblei	BH	unconformity
			shale
	Cristellaria	***CI***	thin sands
	Cibicides carstensi opima	***co***	sand
	Amphistegina	***AB***	shale
	Lower		
	Robulus	***RL***	marine sand
	Operculinoides	OP	bituminous limestone
	Cibicides	CA	sand and shale
	Marginulina ascensionensis	***MA***	sand
			shale
	Siphonina davisi	SD	thin sand
	· · · UNCONFORMITY - - -		
	Anahuac ***(Discorbis)***	***DR***	***shale***
	Oligocene		
	Heterostegina	H	coral reef
	Marginulina howei	***MH***	sand
			shale
	Frio	F	sands
	Cibicides hazzardi	CH	marine sands
	· · · UNCONFORMITY - - -		
	Hackberry facies	HB	geopressured shale
	Vicksburg	vx	black shale

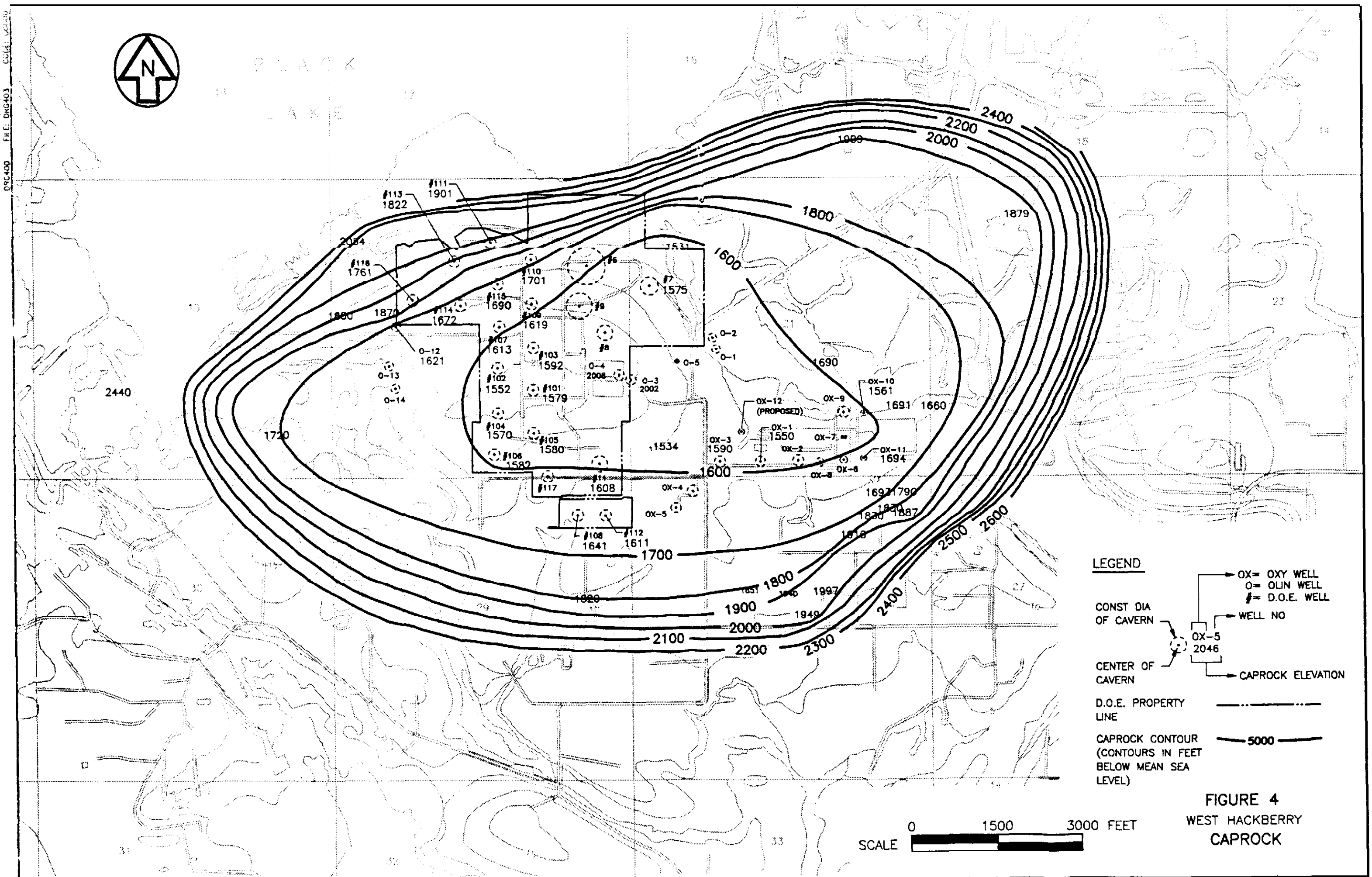


FIGURE 4
WEST HACKBERRY
CAPROCK

It lies on top of flat salt across the dome, as a result of the leaching of salt to a flat surface by groundwater as the dome rises through the overlying sediments. The relatively insoluble anhydrite accumulates as a cap and, in the presence of methane gas seeping up the face of the dome, is partly converted to carbonate. The continued upward movement of the salt with leaching to a flat surface creates a complexly-faulted and fractured domal- to flat-topped cap containing extensive interconnected voids ranging from small vugs to caves.

The caprock at West Hackberry is relatively thin (-400 ft) and limited in aerial extent. It does not overdrape the steep sides of the dome, as occurring at the next dome north, Sulphur Mines -- a small, round conical dome.

Most of the SPR caverns are located near the middle of the dome where caprock conditions are relatively uniform. However, Cavern 111 is located near the steep outer edge of the salt, at the feather edge of the caprock (Figures 5, 6). The subsurface control near Cavern 111 is limited. The closest wells drilled into the solid salt face are in Section 19 to the west and Section 16 to the northeast. The intervening control includes one well that included salt-mineralized sands at a depth of approximately 3000 ft, indicating that it is close to the salt face, as shown on the cross-section (Figure 6). The resultant interpretation as shown on the salt map (Figure 7) is sufficiently straight, except for the radial fault believed to be related to a possible shear zone, to make the cavern quite secure despite the evidence for an overhang. The seismic surveys, while incomplete, support this interpretation, as does gravity data.

If oil leakage from the storage caverns were to occur it would migrate into the caprock and join the much larger volume of oil which has migrated up the face of the salt dome. Although no commercial wells have been completed in the caprock at this dome due to its relatively low porosity, the thin overlying sands are oil productive and adequately sealed from the surface by more than 200 ft of mud. However, gas may leak through these muds. The gas accumulation under the brine pond liner is apparently biogenic, originating possibly from unscarified decaying grass [Ref. 151, but at other domes is indicative of escaping hydrocarbons. Shallow domestic water wells nearby also make gas. Thus, the risk of environmental contamination through migration paths already naturally filled with hydrocarbons may be moot.

Lost circulation: The hydrology of caprock is controlled by the large voids created in the solution process. Although the water is saturated in carbonate throughout, in sulfate half-way down, and is saturated brine at the base, the flow is sufficient to keep the top of the salt very nearly flat. Hydrologic calculations of the rate of salt solution (which must be close to that of intrusion inside the dome) were made at Bayou Choctaw and found to be in agreement with the geologic data of uplift on the flanks.

Thus, lost circulation is to be expected while drilling caprock, although the problem is less in thin caprock here than, for example, at Big Hill where the caprock is one of the thickest known in the Gulf Coast.

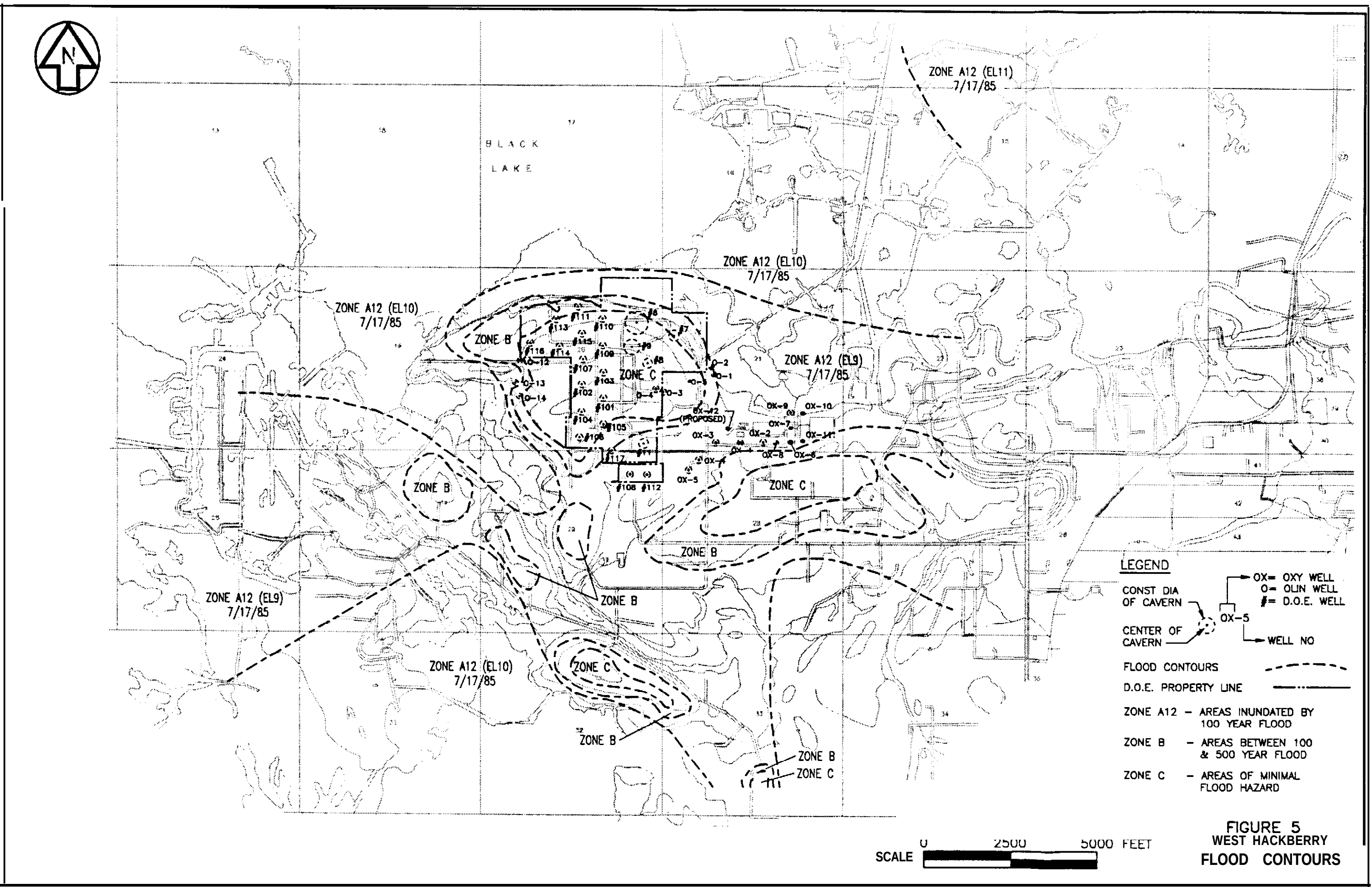
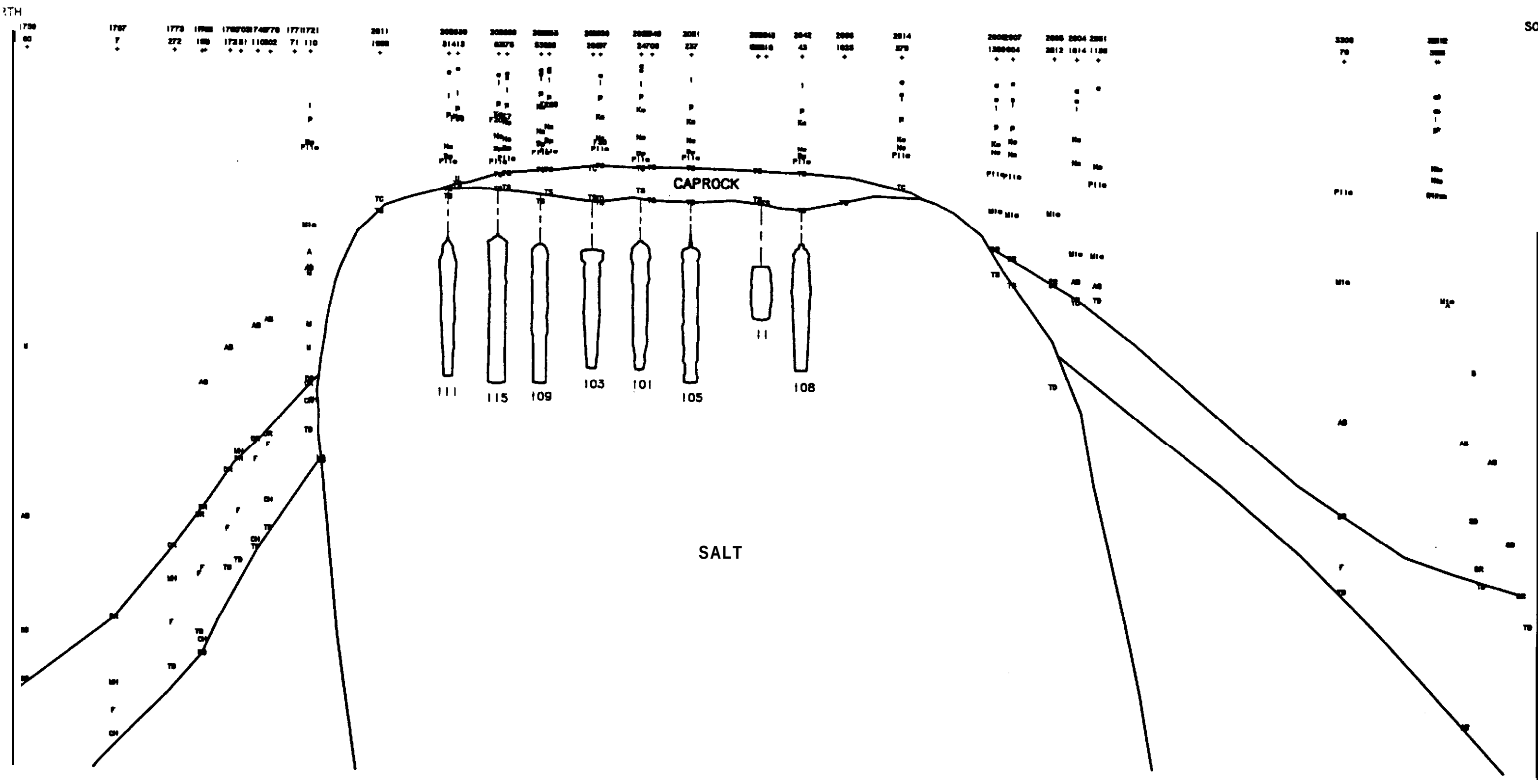


FIGURE 5
WEST HACKBERRY
FLOOD CONTOURS



NOTE: REFER TO TABLE I FOR
STRATIGRAPHIC SYMBOLS

FIGURE 6
(SECTION LOCA
ON FIGURE 2)

WEST HACKBE
SECTION C2
V:H = 1:1

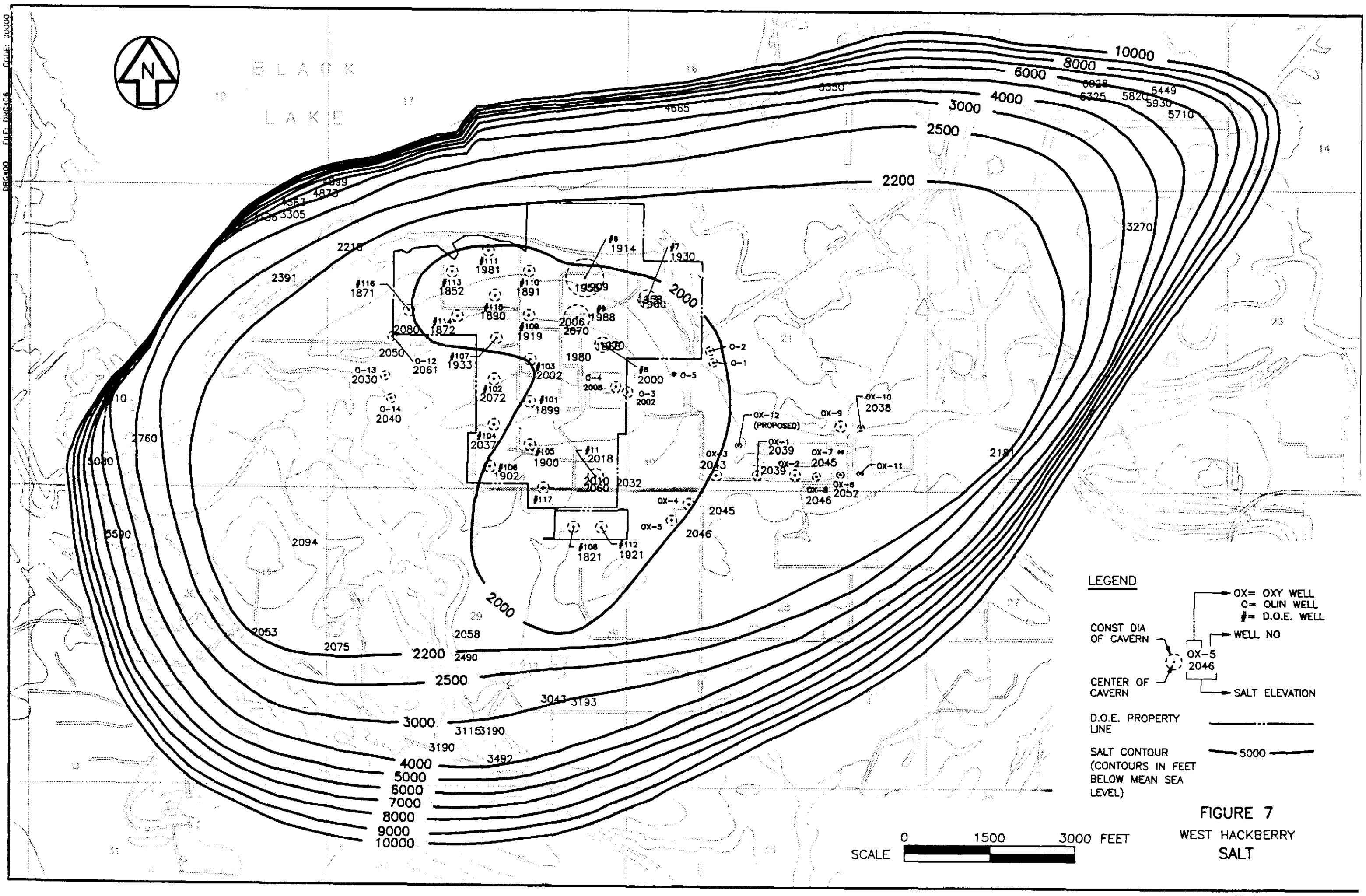


FIGURE 7
WEST HACKBERRY
SALT

The most cost-effective method of penetrating the caprock has clearly been demonstrated to be drilling without returns. By using water instead of mud to cool the bit, hole can be made in this brittle rock without cementing every few feet, once casing is set in the hard carbonate caprock.

lJvdroeen Sulfide: West Hackberry may have significant concentrations of hydrogen sulfide. This toxic gas, commonly known in oilfield terminology as "sour gas," is formed in the reaction of hydrocarbons with anhydrite to form carbonate caprock and sulphur. Although sulphur exploration was not commercially successful, there are abundant shows of sulphur at the top of the anhydrite cap, particularly in the usual location near the rim of the dome. West Hackberry has been prospected and is close to many domes that have produced commercial sulphur, including High Island, Fannett and Spindletop [Ref. 41.

As a result hydrogen sulfide is detectable $n most salt-dome caprocks [Ref. 51. The presence of hydrogen sulfide complicates drilling through the hard caprock because everything in the hole, including the drill string, turns black and corrodes. Any pipe harder than API (American Petroleum Institute) Class E is subject to brittle failure under normal fatigue loads, particularly when corrosive saturated brine must also be used (to drill into salt). Nickel and manganese, used to harden the steel, are more subject to sulfide corrosion and cracking than even iron.

Faults: Caprock is characteristically faulted in most of the cores that are recovered, so much so as to be a permeable jumble of broken blocks with secondary calcite cementation. Some of these faults extend to the surface, and may control subsidence as well as localize small, natural shallow oil accumulations. The faults are further suggested by the shape of the triangular subsidence trough [Ref. 181, and by the producing wells on higher blocks across the top of the dome.

The active shallow faults originating in the caprock or salt shear zones have only displaced the Recent sediments a few feet. They do not pose any apparent risk to the storage caverns by themselves, but subsidence along them could conceivably damage surface facilities or well casing, as has occurred at other domes used for storage of (LPG) products, e. gap Stratton Ridge, TX [Ref. 61.

Salt

The general shape of the combined East and West Hackberry domes, a flat-topped and slightly-tilted ellipsoidal cylinder, is similar to that of most elongated salt domes. In the case of Hackberry, the tilt is northward. The west end is relatively blunt and the east end, at the saddle to East Hackberry, sharply pointed (Fig. 7). This disagrees significantly with the earlier interpretations [Ref. 11, which included a deep valley on the north side and an elongate conical dome. As a result, several significant revisions in the external geometry of the salt stock were required in revising the dome contours.

Commercial exploratory drilling was very limited in the area from 1986 to 1991 because of the decline in oil prices, so little new data has been available, although a few old wells have been twinned to keep up production. The steep southeast face along with the sharp east end suggests that a transform or wrench fault separates the domes.

Studv Method; Sediment structure around the dome is used in this study to help define the salt face. Methods of determining the salt face include dip and convergence or thinning of the beds uplifted by the salt intrusion.

Asymptotic Dip: From flat beds in the bottom of the rim syncline, the dips of the sediments around the salt increase 65 degrees in many places against the near-vertical face. This asymptote allows the horizontal position of the salt face to be calculated from the observed change in dip.

Convergence: In addition to structure, as discussed below, stratigraphic variation is used in this study to help define the edge of the salt. That is, the intersection point at which projected beds meet is a good estimate of the salt face. There is extreme convergence in the Oligocene with its thick shales but very little convergence in the overlying Miocene Sands. The resultant thinning is particularly apparent in the oil-productive Frio sands.

Rate Of Uplift: The overall average intrusive rise of the dome as a whole can be calculated from the uplift of dated marker beds that are asymptotic to the face of the salt. The deepest penetrated, Hackberry shale sheath (HB), some 40 million years old (my), has been uplifted some 7000 ft, the top of the Oligocene (DR, 30 my) 6000 ft, middle Miocene (AB, 15 my) 3000 ft, Miocene (10 my) 2000 ft. Pliocene (2 my) 500 ft, and Peorian (p, 0.5 my) 100 ft. These values are all very close to a rate of 0.1 mm/yr, which is the same as that obsenred at Bayou Choctaw and Big Hill. This rate is exceeded only by the Five Island Chain, including Weeks Island, which has an apparent uplift rate as high as 4 mm/yr.

Snines: The spine theory of salt intrusion and its validation in mines is reviewed in the Weeks Island SPR Geological Characterization Report [Ref. 73. The well log data and their correlation at Weeks shows two spines separated by a shear zone in the south half of the dome used by SPR. The spines are interpreted as anticlinal features or domes in the anhydrite correlation data at Big Hill [Ref. 81.

In east-west domes like West Hackberry, the salt flow likely occurs in widely-separated spines. However, there is insufficient control within the salt to define these spines by their shear zones, i. e., areas of more anhydrite which separate them. The holes that were drilled to leach the new DOE caverns were only partially logged and a few cores cut. Only one hole per cavern was drilled (except 117, which has two) and logged through the salt, so that it was not possible to use the methodology developed at Big Hill for mapping anhydrite bands and thereby the internal structure of the salt intrusion. Consequently, any additional cavern development should require exploratory drilling and logging to delineate such features within the salt mass, even though specific effects on cavern construction may be speculative.

Core samples show that the salt is relatively dark with considerable disseminated anhydrite, even in the middle of apparent spines. The salt crystals are tightly interlocked, as a result of the compaction due to the weight of the caprock. This dark salt, believed to be less recrystallized since uplift, is typical of slower-moving domes.

Shear Zones: All salt domes that have been studied have their shear zones centered on and parallel to the underlying salt ridges. The shear zones are always between the spines. They are observed as a high concentration of near-vertical anhydrite and other inclusion bands, usually reflected as a sharp trough or low on the surface of the salt. Sediment trapped between the spines in an overhang could be incorporated into the salt dome by continued intrusion, creating potential problems if cavern leaching is attempted across shear zones'.

The postulated northeast-southwest shear zone correlates very closely with the fault running into the overhang (Figures 8, 9). A secondary shear zone normal to this appears to cross it over the center of the dome, somewhat like Weeks Island. This complication may be related to the apparent steep dips in Miocene sediments near the northwest comer where a radial fault ties in with the apparent shear. This shear zone also represents the axis of the salt ridge upon which the dome sits.

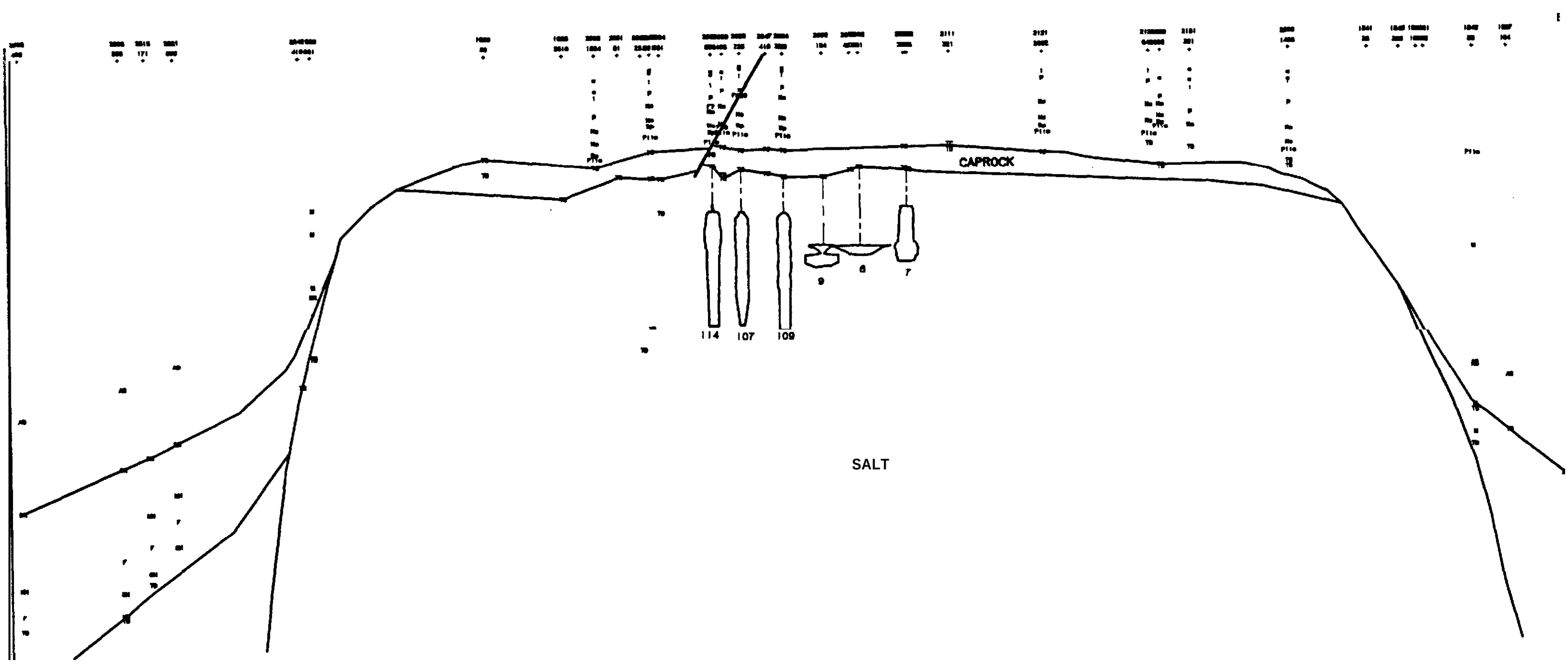
The partial, near-vertical overhang on the north side adjacent to the site is a much-less complete seal, requiring lateral sealing along the shear zone which has acted as a fault beyond the edge of the salt stock. It is unlikely, however, that all the oil and gas trapped against this salt dome have been found.

Well Control

Significant drilling has been done close to the salt face around the dome since the original geologic characterization. Amoco has drilled two additional wells downdip in the productive salient at the southwest comer of the dome which do not change the interpretation of the salt face. All of the available well data are included in the appended Well Tables (Appendix D). A long overhang may limit the depth and extent of caverns in a broad arc across the north side of the DOE property. This overhang is very nearly vertical, like the north side of Weeks Island and the West side of Bayou Choctaw, and unlike the 60 degree overhang on the south side of Big Hill.

Seismic Data

The original seismic data from 1983 was obtained under contract by Woodward Clyde Consultants, Inc. However, the lines were not extended out into Black Lake far enough to get good reflections from the steep salt



NOTE : REFER TO TABLE I FOR STRATIGRAPHIC SYMBOLS

FIGURE 8
(SECTION LOCAT
ON FIGURE 2)

WEST HACKBER
SECTION CI
V:H = 1:1

KOB 10/28/91 P0798412
FILE: DRG100 CODE: 00000

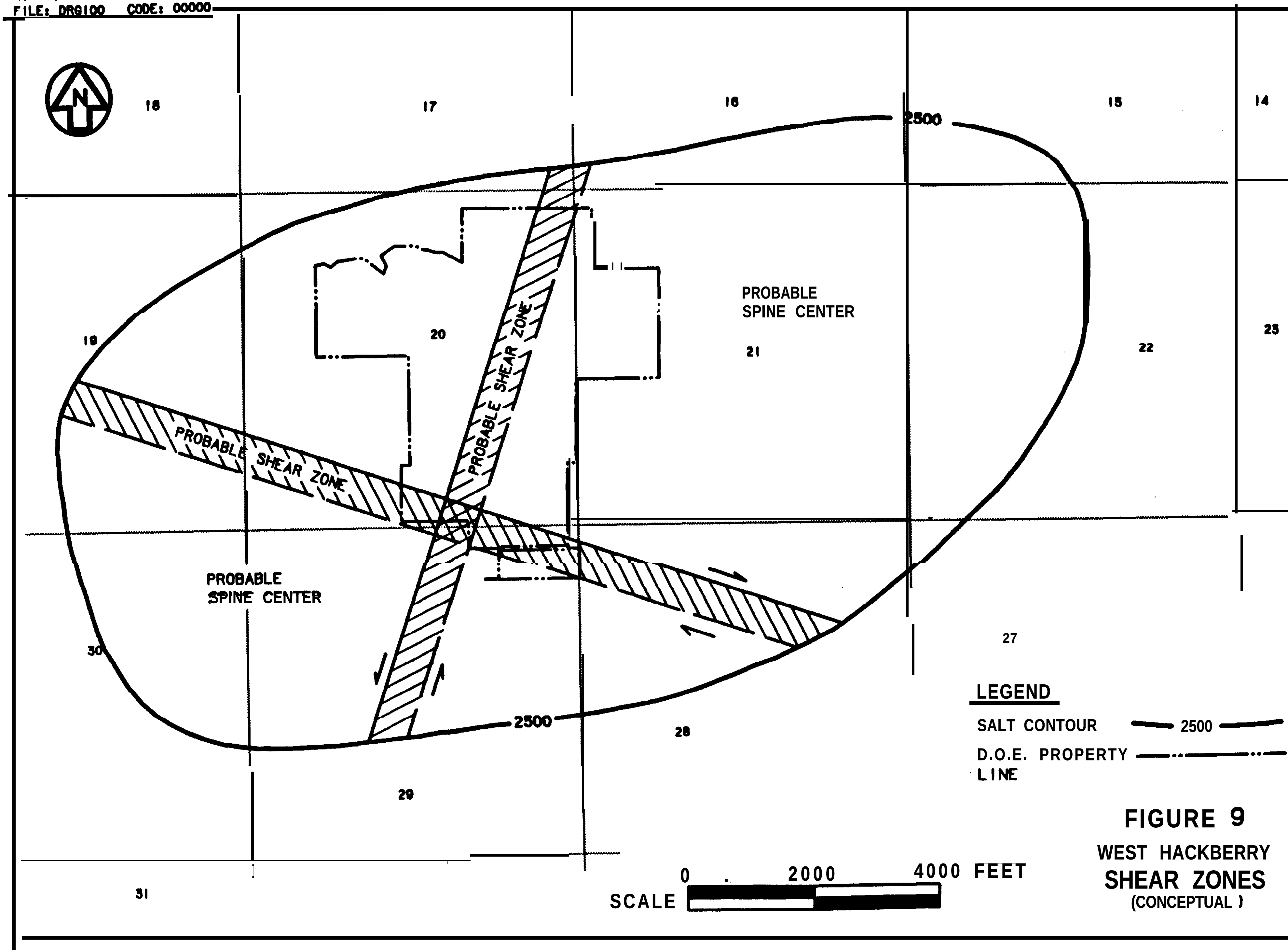


FIGURE 9
WEST HACKBERRY
SHEAR ZONES
(CONCEPTUAL)

27

face and its flanking sediments. The only data is from the top of the cap and salt.

Amoco data is available, possibly indicating an overhang. The critical line, closest to Cavern 111, was to have been reprocessed in early 1991 to help resolve the overhang uncertainty, but with lower oil prices apparently has been delayed indefinitely.

Amoco gravity data was examined to improve the interpretation of shallow faults, salt spines, and possibly subsidence. The data support the overall interpretations reported on here,

Salt Contours

The salt contours (Figure 7) were fitted to the digitized database using more than 50 cross-sections, smoothed both horizontally and vertically between the faults found in well cuts (in the oil-bearing and overlying sediments near the salt). The most important changes in the shape of the dome from previous maps are the overhang and faults on the north side, next to the SPR storage site.

Most of the shape of the rest of the dome, connecting to East Hackberry in a neck protected by shale, is smoother than previously mapped since we have shown that the shallow solution topography on the top of the dome is unrelated to the steep flanks which have never been systematically contoured via computer graphics with a digital database.

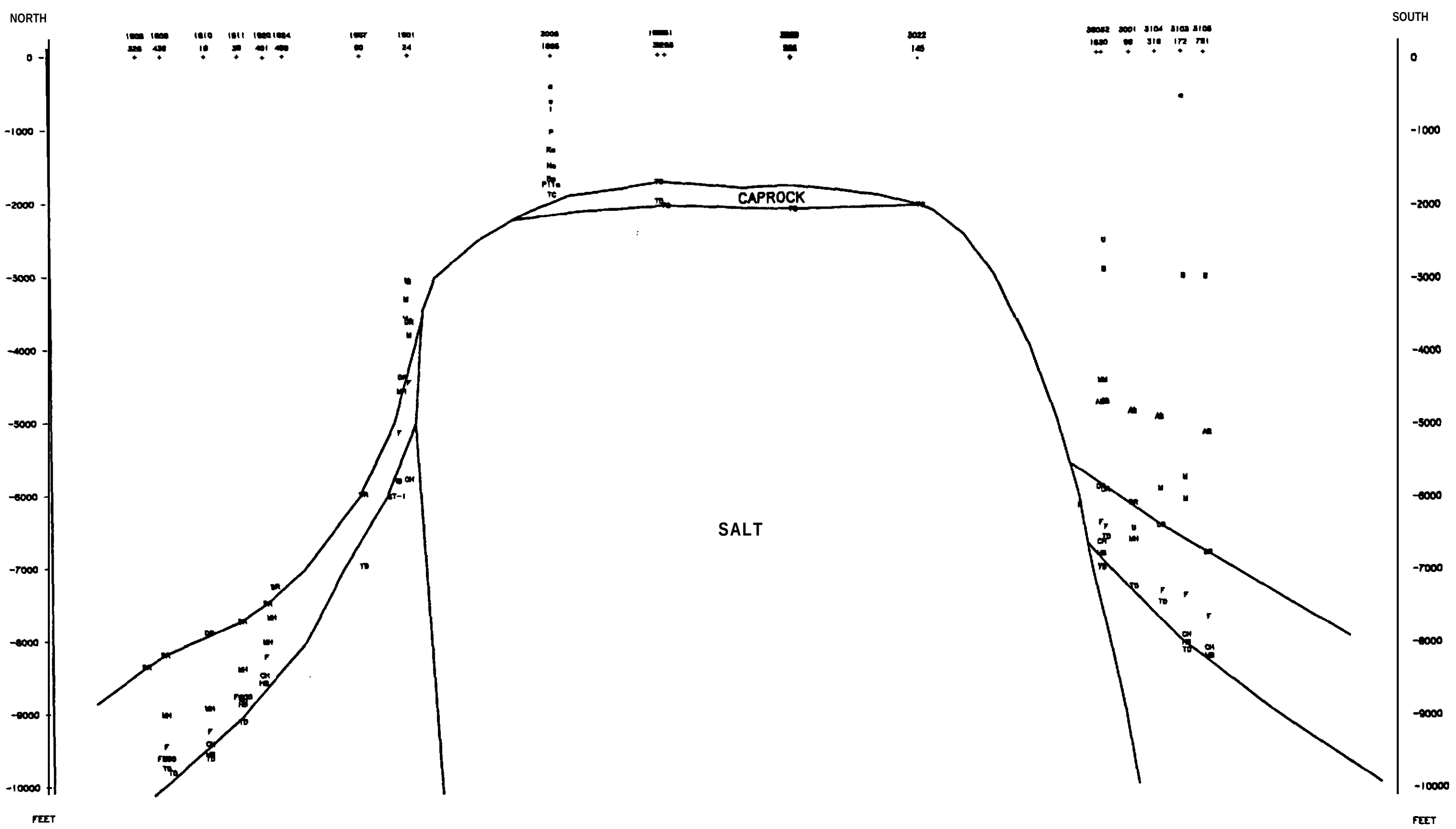
An east-west and three north-south cross-sections (Figures 6, 8, 10, and 11; located on Fig. 2) have been prepared from the digitized database for this report. The two westernmost north-south sections show clearly the overhang just north of the SPR site.

The westernmost section (Figure 10) shows the northwest comer of the dome where the complex near-vertical Frio sands have been dragged up to almost cover the shoulder of the dome. The oil has leaked up into the basal Miocene sand, and probably from here into the sands above the caprock. A similar complex area is found in the same position at Weeks Island where the near-vertical sands are basal Miocene age.

The middle north-south section (Figure 6) through the SPR caverns shows the normal 60 degree dips extending nearly a mile out from the salt overhang, providing most of the oil production.

The easternmost section (Figure 11) shows a wide band of geopressured Hackberry shale truncated by the unconformity at the top of the Oligocene which protects the salt face, suggesting a large area of undeveloped storage potential.

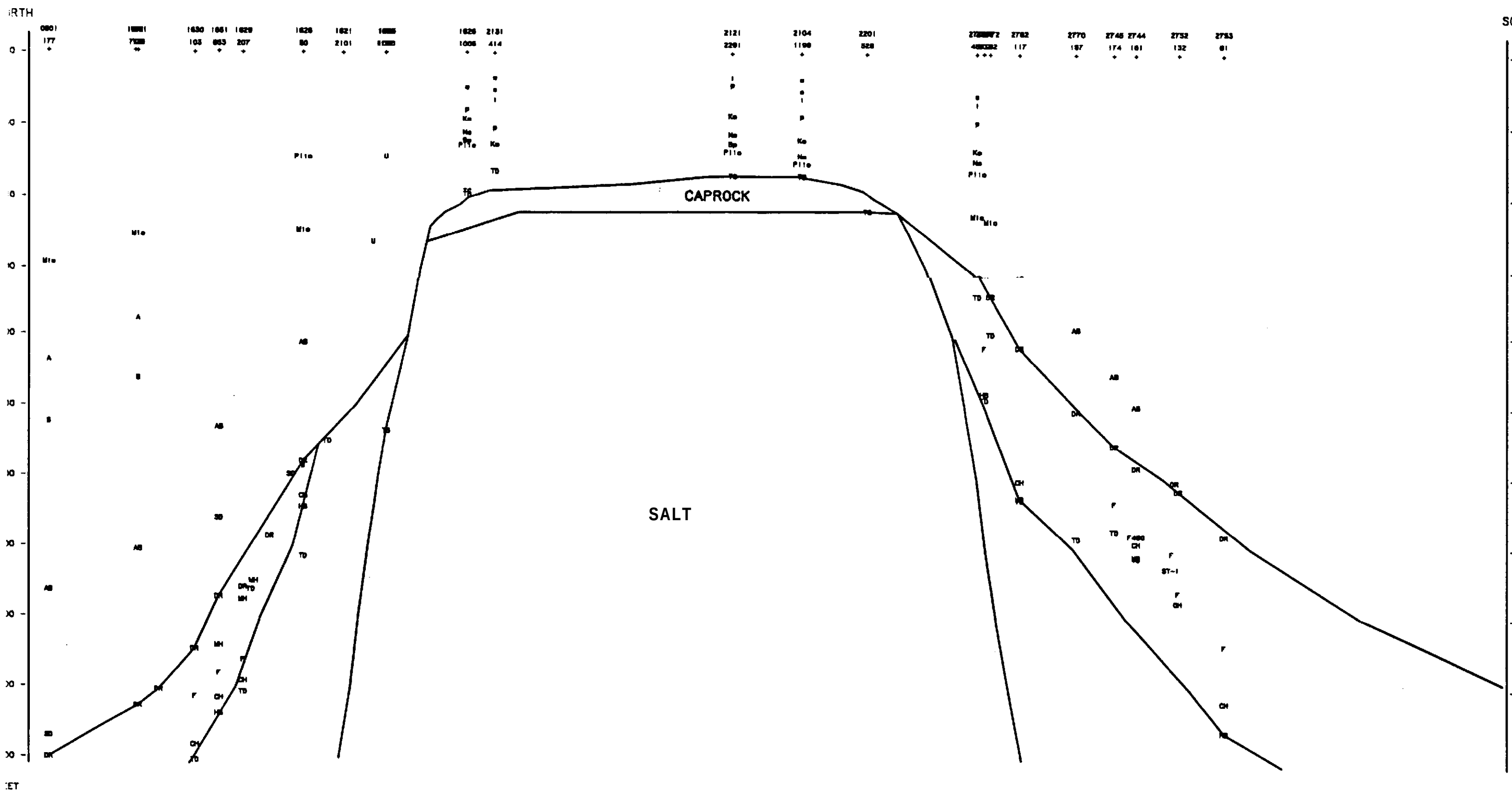
The east-west section (Figure 8) runs the length of the dome, crossing the SPR storage area and showing one of the faults believed possibly



NOTE: REFER TO TABLE I FOR STRATIGRAPHIC SYMBOLS

FIGURE 10
(SECTION LOCATION ON FIGURE 2)

WEST HACKBERRY SECTION C3
V:H = 1:1



NOTE: REFER TO TABLE I FOR STRAT GRAPHIC SYMBOLS

FIGURE 11
(SECTION LOCATION ON FIGURE 2)

WEST HACKBERRY
SECTION C4
V:H = 1:1

activated by cavern creep and bounding the triangle of greatest surface subsidence. This fault is the surface expression of a probable shear zone separating active spines. It shows on both salt and caprock maps. We have no evidence that any of these faults intersect the caverns, or the well casings.

St-ctural 1ntemretatW.i

Dome-Related Fault- The shear zone observed in the new wells continues outside the salt as the single radial fault on the dome (Figures 1, 2) that is oil productive, having been substantiated at the northwest comer of the dome and discussed earlier under the section on shear zones.

The West and East Hackberry Salt Domes, along with the Big Lake structure to the east, form an east-west ridge in the middle of the Hackberry embayment, the most prominent Frio feature of the Gulf Coast. It is a large depression that was filled in Oligocene middle Frio time with deep-water shale. Big Hill, a previously characterized SPR dome, lies on the west edge of the embayment [Ref. 81.

The rim syncline surrounding the salt ridge represents the equilibrium in the intrusive salt between the sands being deposited from the northwest and the Hackberry Rmbayment.

SPR SYSTEM CONSIDERATIONS

The effects of regional and local geology may affect the SPR operations in a variety of ways. These aspects are discussed in the following pages.

Cavern Configuration

The five caverns which were purchased from the Olin Corp., WH 6, 7, 8, 9, and 11, existed at the time of the 1980 site characterization. The geometry of these caverns is unchanged, but refinements in some of the technical data have been made; these changes are indicated in Table 2, along with the data from the 17 new caverns, WH 101-117. Caverns WH lOl-' 116 are single-well caverns, whereas WH 117 is a two-well cavern, similar to the Phase III caverns at Big Hill.

Table 2 was compiled by Boeing Petroleum Services and lists the most relevant parameters associated with cavern integrity. All depths are given in feet below the bradenhead flange (which varies from 4 to 19 ft amsl), but cavern-induced subsidence is gradually lowering the mean sea level values. A brief description of the data follows:

"Cavern number" is shown on Figures 5 (base map), and 13 (air photo)

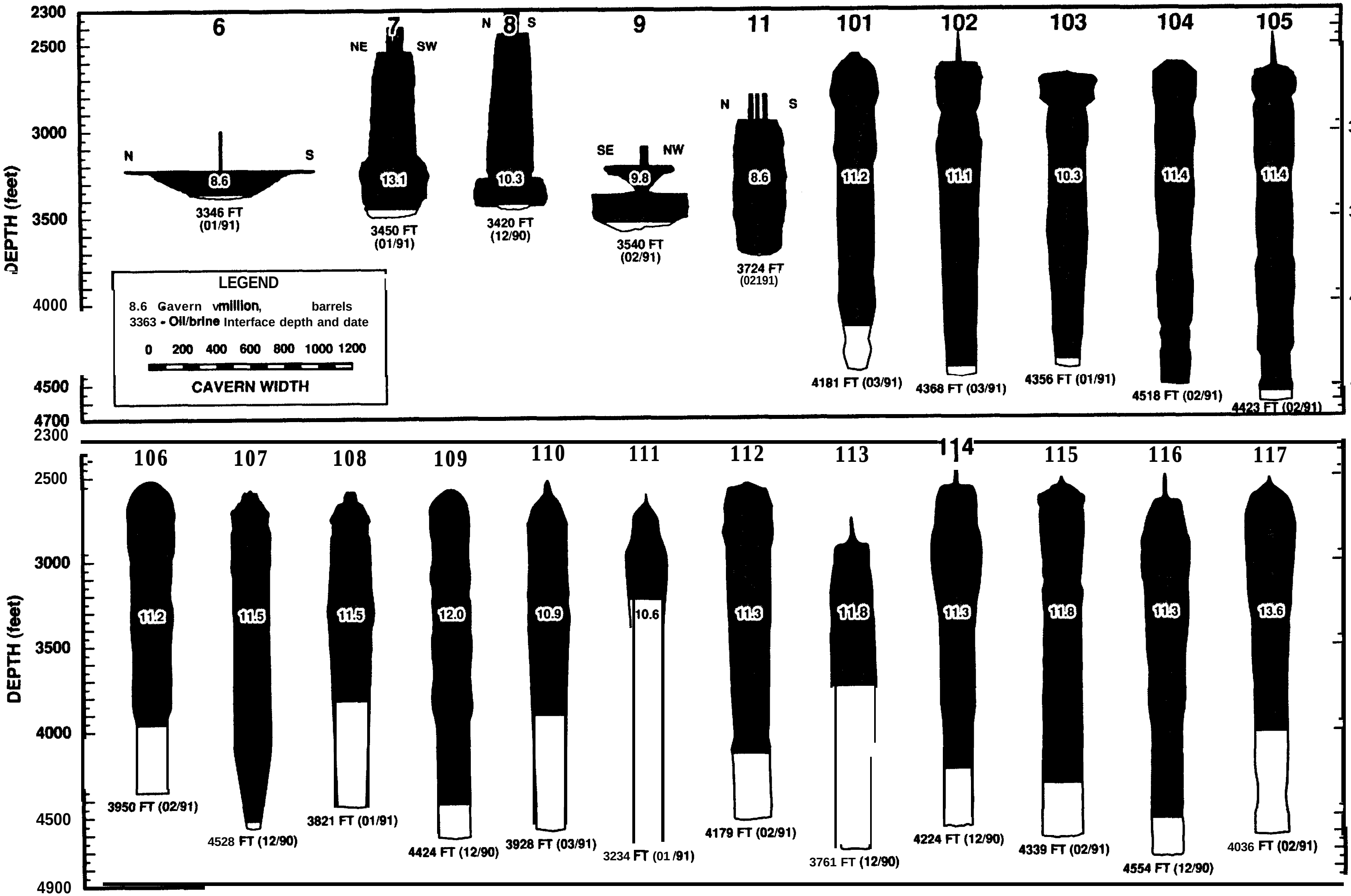
"Date constructed" indicates time of leaching, but does not include workovers, etc., performed subsequently.

TABLE 2: WEST HACKBERRY CAVERN GEOTECHNICAL PARAMETERS

DataCurrentto6/05191

Cavern	Date Constructed	Cavern Volume, MMB	Top Caprock	Top Salt	Casing Seat	Top Cavern	Bottom Cavern, Date	Cavern Height (H)	Diameter (D)	H/D	Nearest Cavern	Pillar Thickness(P)	P/D	Roof Thickness (B)	B/D	Distance to Dome Edge(E)	E/D	Distance To Property Line	BHF Elevation, 1966
6	1946	6.6	-1596	-1949	-2562	-3249	-3390, 01/91	141	662	0.21	9	331	0.50	1300	1.96	480	0.73	350	5.2
7	1946	13.1	-1551	-1992	-2393	-2552	-3494, 01/91	942	315	2.99	6	609	1.93	560	1.76	1650	5.24	189	4.3
6	1946	10.3	-1515	-2035	-2337	-2450	-3449, 12/90	999	272	3.67	9	149	0.55	415	1.53	1700	6.25	239	13.2
9	1947	9.6	-1550	-2100	-2525	-3213	-3555, 02/91	342	454	0.75	6	149	0.33	1113	2.45	1206	2.64	744	11.8
11	1962	8.6	-1529	-2085	-2790	-2951	-3756, 02/91	804	276	2.92	106	567	2.05	866	3.13	2500	9.06	349	10.9
101	05/81-12/83	11.2	-1609	-2050	-2434	-2555	-4440, 03/91	1885	206	9.15	103	397	1.93	505	2.45	2600	12.62	735	18.7
102	02/82-11/84	11.1	-1621	-2063	-2440	-2628	-4498, 03/91	1870	206	9.08	103	448	2.17	565	2.74	2210	10.73	122	15.8
103	05/81-01/84	10.4	-1558	-2038	-2432	-2667	-4423, 01/91	1756	205	a.57	101	397	1.94	629	3.07	1900	9.27	746	16.0
104	05/81-02/84	11.5	-1561	-2076	-2450	-2625	-4546, 02/91	1921	206	9.33	102	450	2.18	549	2.67	3000	14.56	101	17.7
105	01/81-01/84	11.5	-1647	-2058	-2458	-2640	-4609, 02/91	1969	204	9.65	1o4	492	2.41	582	2.85	3000	14.71	641	17.7
106	01/84-08/87	11.3	-1660	-2665	-2402	-2556	-4346, 02/91	1790	212	a.44	104	492	2.32	491	2.32	1560	7.36	154	16.2
107	07/81-07/84	11.5	-1608	-2058	-2473	-2585	-4556, 12/90	1971	204	9.66	103	470	2.30	527	2.58	1510	7.40	149	14.5
108	02/82-12/84	11.5	-1664	-2053	-2420	-2596	-4440, 01/91	1a44	212	8.70	112	513	2.42	543	2.58	1700	8.02	144	7.5
109	03/84-11/85	12.0	-1606	-2057	-2469	-2583	-4644, 12/90	2061	204	10.10	9	386	1.89	526	2.58	1000	4.90	820	9.3
110	02/82-03/85	11.2	-1683	-2072	-2430	-2567	-4568, 03/91	2001	200	10.01	111	520	2.60	495	2.48	400	2.00	206	6.7
111	01/82-04/88	10.6	-1980	-2180	-2534	-2622	-4596, 01/91	1974	196	10.07	110	520	2.65	442	2.26	500	1.53	loo	6.9
112	09/83-01/87	11.4	-1650	-2050	-2437	-2562	-4532, 02/91	1970	203	9.70	108	513	2.53	512	2.52	1800	8.87	157	7.9
113	07/82-06/85	12.2	-1920	-2113	-2772	-2827	-4692, 12/90	1a65	216	8.63	114	518	2.40	714	3.31	500	2.31	106	6.2
114	09/82-09/85	11.3	-1668	-2073	-2380	-2520	-4549, 12/90	2029	200	10.15	113	518	2.59	447	2.24	1000	5.60	213	6.1
115	02/84-06/87	11.8	-1713	-2073	-2456	-2540	-4634, 02/91	2094	201	10.42	107	478	2.38	467	2.32	900	4.48	636	7.7
116	07/82-09/85	11.5	-1773	-2088	-2520	-2640	-4718, 12/90	2078	199	10.44	114	542	2.72	552	2.77	1100	5.53	180	8.9
117	06/85-09/88	12.7	-1594	-2051	-2412	-2560	-4609, 06/90	2049	211	9.71	108	421	2.00	so9	2.41	2100	9.95	241	13.7

FIGURE 12. GENERALIZED CAVERN CONFIGURATIONS, WEST HACKBERRY SPR SITE



TA0188.01.23

"Cavern volume," in millions **of** barrels, is usually about 100 larger than the volume **of** stored material, allowing for brine in the cavern bottom.

'Top of caprock and salt," respectively, are the uppermost surfaces of those units.

"Casing seat," and "cavern top (or bottom) is self-explanatory.

"Cavern Height (H)" is the distance from cavern top to bottom.

"Diameter (D)" is the constructed diameter, which is an idealized (average) cylfnder diameter that would correspond to the final cavern volume with the given height.

*H/D" is the ratio-of the cavern height to the constructed diameter, providing a measure of the cavern shape.

"Pillar thickness (P)" is the thickness of the pillar of salt between a cavern and its nearest neighbor.

"P/D" is the ratio of the pillar thickness and the constructed diameter, providing a relative measure of mechanical integrity.

"Roof thickness (B)" is the distance between the top of the cavern and the top of salt.

"B/D" is the ratio of the roof thickness to the constructed diameter, providing a measure of mechanical integrity.

"Distance to &me edge (E)" is the estimated distance between the cavern and the outside edge of dome salt.

"E/D" is the ratio of the distance to the edge of dome to the constructed diameter, providing a measure of mechanical integrity.

"Distance to property line" is the closest distance between the cavern edge and the SPR property line.

"BHF Elevation" is the bradenhead flange elevation in 1988, rounded to 0.1 ft.

The values shown in Table 2 reflect the very conservative design approach used throughout the SPR system, especially for Caverns WH 1010 117. The preexisting caverns (WH 6-11) do not follow those same guidelines, of course, but there have been no stability or safety issues with them.

Cavern ShaDes

Figure 12 shows current cavern shapes by best estimates. Caverns WH 6111 are quite well mapped, having been sonar surveyed when filled only

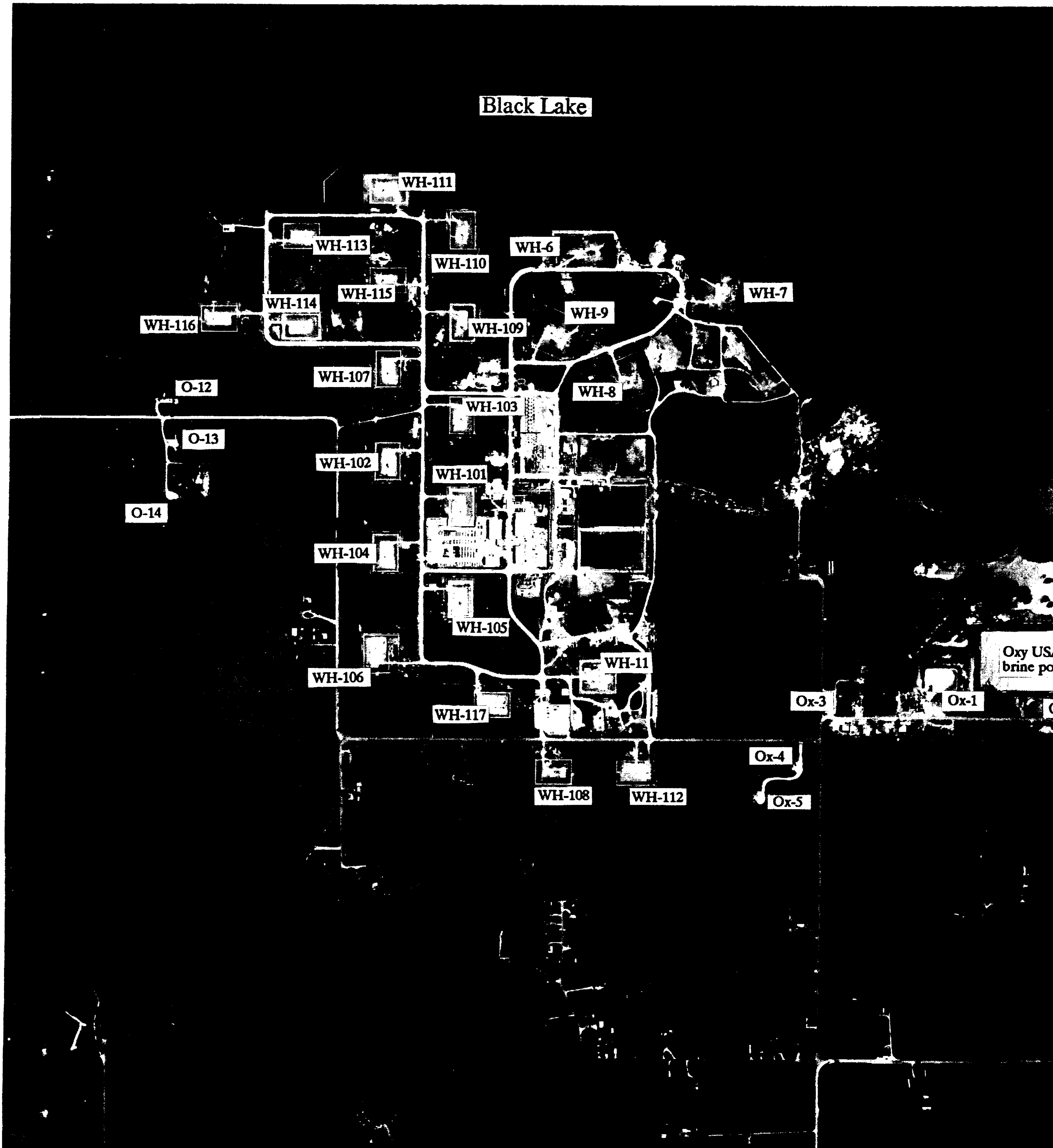


Figure 13 Vertical airphoto, showing principal surface features and cavern locations. 10 May 90, scale 1:12,000.

with brine. However, data used to compile cavern shapes for WH 101-117 were derived from sonar records obtained during cavern development, and from oil fill and interface records obtained during leach and fill operations. Because sonar recordings could not be obtained through oil, the oil fill vs volume data result in axisymmetric cavern shapes on the drawings, whereas in fact they are not. Nonetheless, the data and sonar records obtained during cavern development show very symmetrical cavern shapes for the new caverns (WH 101~117), suggesting there is a general absence of significant mineralogical or structural effects that have resulted in preferentially oriented caverns. Cavern WH 111 is a notable exception, with pronounced assymetry in the top 200 ft.

Cavern WH 6 is somewhat saucer-shaped, with a diameter of nearly 1200 ft and a height of about 140 ft. The aspect ratio of 0.21 (using the constructed diameter) is the lowest in the SPR system and there has been concern over possible collapse of the cavern roof. However, the twelve-plus year history of SPR operations combined with the former 32-year history of Olin's brine feedstock extraction attests to its long-term stability. The September 1978 blowout and fire at this cavern was unrelated to the low aspect ratio [Ref. 91.

Cavern WH 9 has two lobes separated by a -60 ft neck at about 3370 ft depth. The salt ledges here are a potential source for salt falls which could damage hanging strings but this has not occurred.

Caverns WH 101-117 are for the most part unremarkable, and significant deviations from design shapes have not occurred. Caverns W 101, 102, and 103 have slightly wider tops than an ideal tapered cylinder, and Cavern WH 111 has a small ledge, or shoulders, near the top. The small diameter above the shoulders was deliberately caused by filling with oil during the last leaching stage to prevent further growth. These minor departures have no bearing on cavern operation and present no safety or integrity concerns. Cavern WH 113 was constructed with the last cemented casing set 270 ft deeper than the other Phase II wells. This resulted in a slightly deeper cavern top and the cavern height was reduced somewhat, so that the nominal top and bottom are at 2800 and 4700 ft, respectively [Ref. lo].

Cavern 112 originally was to have been constructed just west of Cavern 113 but exploration revealed a re-entrant and fault structure in the salt face along the north side of the dome, resulting in insufficient distance to the edge of salt and requiring that the cavern be re-located south of Cavern 11 (Figure 13).

Additional Cavern Snace

In the event it would become necessary to abandon one or more of the existing caverns, or to transfer oil for some reason, there is probably room for another cavern just outside the DOE property northeast of Cavern WH 11 and southeast of abandoned Olin Caverns 3-4 (coalesced). To verify that sufficient pillar space exists at this location, the former Olin caverns would need to be opened and sonar surveyed. Space for two other Faverns also exists immediately south of Cavern WH 106, and southwest of

Caverns WH 108 and 117, but neither of these locations are presently on DOE property.

Similarly, off of DOE property, just west of Caverns 104, 102, and 107 (Fig. 13), there are possible locations where storage caverns could be constructed, with cavern roofs at -2500 ft or deeper. These depths have already led to greater creep/subsidence rates at West Hackberry, and thLs fact combined with the already low elevation would have to be reconciled.

With the existing cavern volume total exceeding 275 million barrels in 36 existing and five abandoned caverns, the dome is approaching the reasonable upper limit for storage. All of the above considerations would require study prior to serious thought of expansion.

pew Olin Caverns 12. 13. 14

The Olin Chemicals Group completed three brine wells in 1977 to provide feedstock for its chlor-alkali operations at Lake Charles. SPR Cavern 116 is the closest adjacent cavern to this group, 750 ft northeast of Olin #12 (Figs. 5, 13). Figure 14 shows the pillar thickness between the two caverns to be more than 500 ft.

All three Olin wells were identical in design, but minor variations in tubing and cavern depths occur. The three wells produce brine which consumes salt at a rate of about one million barrels (volume) annually. Total cavern volume was 12.72 MMB (from sonar) in October 1989 and 1991 year-end estimates are 15.5 MMB.

1989 sonar records show the caverns as elongated cylinders approximating baseball bats in shape, with the large dimension at the bottom. The highly symmetrical shapes are somewhat questionable because the sonar survey was performed through two hanging strings. At that time the total volume was 12.7 million barrels, with maximum diameters of 188, 178, and 173 ft for Caverns 12, 13, and 14, respectively. All three wells had operated in the bottom injection - top recovery mode, which produces the observed-shape caverns. A December 1989 Olin letter to the Louisiana Office of Conservation, Injection and Mining Division, indicated that its 1989 sonar logging showed the inter-cavern distance between two caverns was 205 ft. So as to not exceed the 200 ft separation specified in Statewide Order #29-M, Olin requested a change in its leach extraction procedure for two of its wells, with the apparent intent of altering the shapes to more regular cylindrical forms.

Because the wells are spaced 390 ft apart, and because the maximum diameters are already being approached in two of the three caverns, there is a limit to how much more extraction of brine is possible, perhaps as much as twice the current total, or roughly twelve years at current rates. Olin management personnel indicated they had no immediate plans for expansion to other locations.

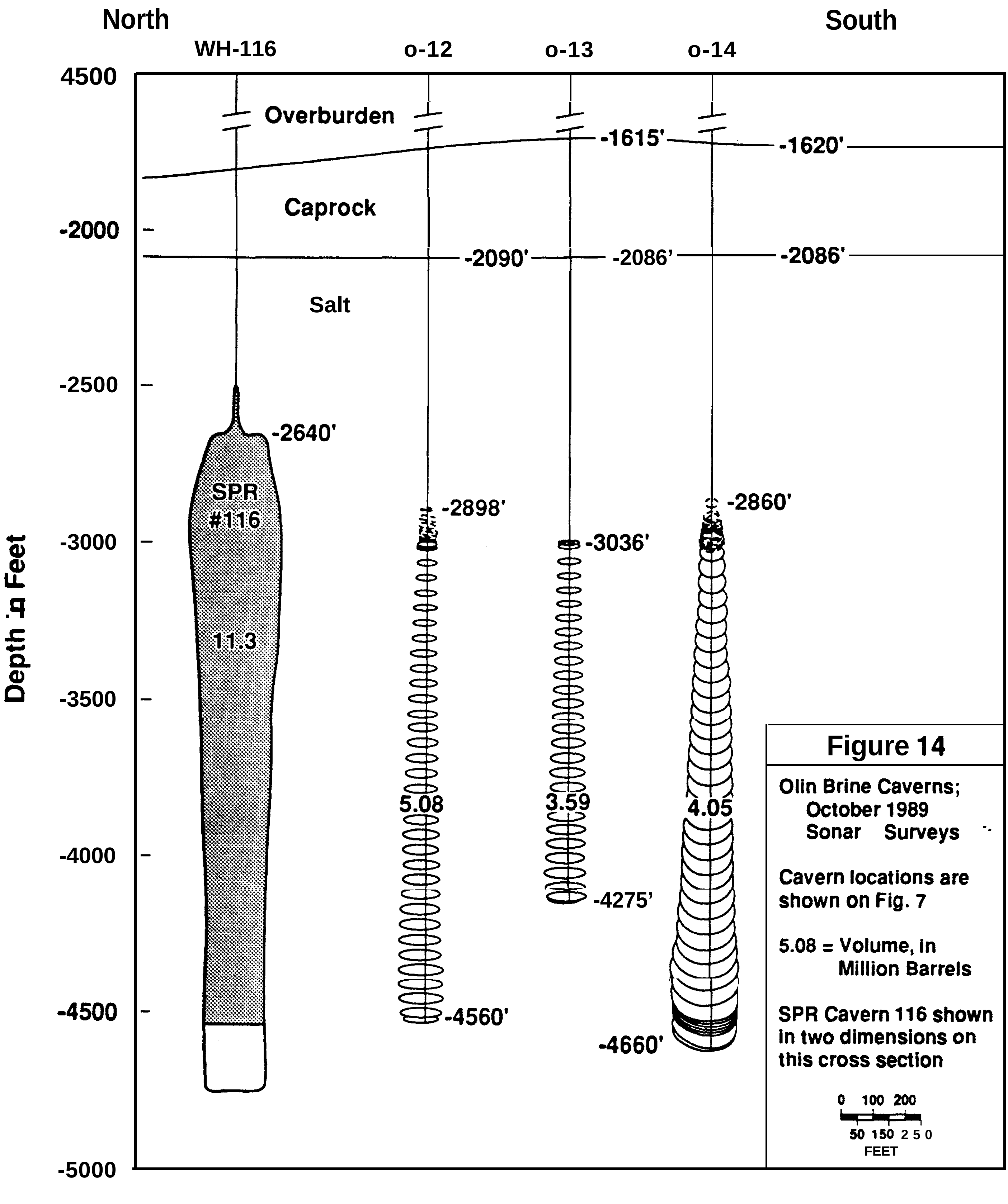


Figure 14

Olin Brine Caverns;
October 1989
Sonar Surveys

Cavern locations are shown on Fig. 7

5.08 = Volume, in Million Barrels

SPR Cavern 116 shown in two dimensions on this cross section

Oxy USA Caverns l-11

Oxy USA, Inc. operates 11 storage caverns containing a variety of LPG products (Figs. 5, 15; Table 3). Total storage volume in mid-1991 was slightly more than 16 million barrels, with individual caverns ranging from 0.86 to 2.77 MMB. Useable storage volume is approximately 14 MMB. Cavern 12 has been permitted, and once constructed will produce brine for several years prior to product storage; its location is north of and centered between caverns 1 and 3.

TABLE 3 -- OXY USA CAVERN DATA: WEST HACKBERRY, LA

Cavern	Volume, MMB	Product	Casing Seat	Total Depth	Diameter, Maximum	Diameter, Constructed	Last Sonar
ox- 1	1.61	Raw	-2252	-2855	249	138	17 May 91
ox- 2	0.98	Citco nC-4	-2254	-2891	244	105	19 Feb 90
ox- 3	0.86	Citco nC-4	-2287	-2873	261	102	14 De 88
ox- 4	1.11	Citco iC-4/BB	-2343	-3030	258	108	27 Mar 90
ox- 5	2.77	Propane	-2366	-3361	248	148	31 Mar 89
Ox- 6	1.66	Ethane	-2352	-3101	181	126	16 Apr a8
ox- 7	0.89	Propylene	-2328	-3175	115	87	08 Mar 90
ox- 8	1.53	fg Butane	-2347	-3106	176	120	30 Aug 89
ox- 9	2.00	Butane	-2345	-3091	273	139	09 Apr 90
ox-10	1.35	fg Butane	-2561	-3583	144	97	03 Aug 90
ox-11	1.40	Propane	-2566	-3383	145	110	15 Apr 88

Cavern shapes as revealed on sonar records are all very symmetrical (Fig. 15), attesting to the uniformity and purity of salt, and the general- lack of non-halite constituents that lead to assymetry. Oxy Cavern 5 is closest to SPR Cavern WH 112; the web thickness between them is 700 ft at the closest approach at -3150 ft. Using constructed diameter values (average cylinders), the average pillar thickness increases to 780 ft.

Subsidence over the Oxy cavern field has been monitored by way of repetitive leveling on some six occasions in the last seven years. The data, while not subjected to detailed scrutiny, show very little, if any, lowering of surface elevations. In view of the substantially less storage volume (6.6% of the SPR total) spread out over 140 acres, combined with substantially more shallow caverns (average depth - 3132 ft), a negligible amount of subsidence is not unreasonable to expect. The effect of cavern depth on subsidence is explained further in Appendix C.

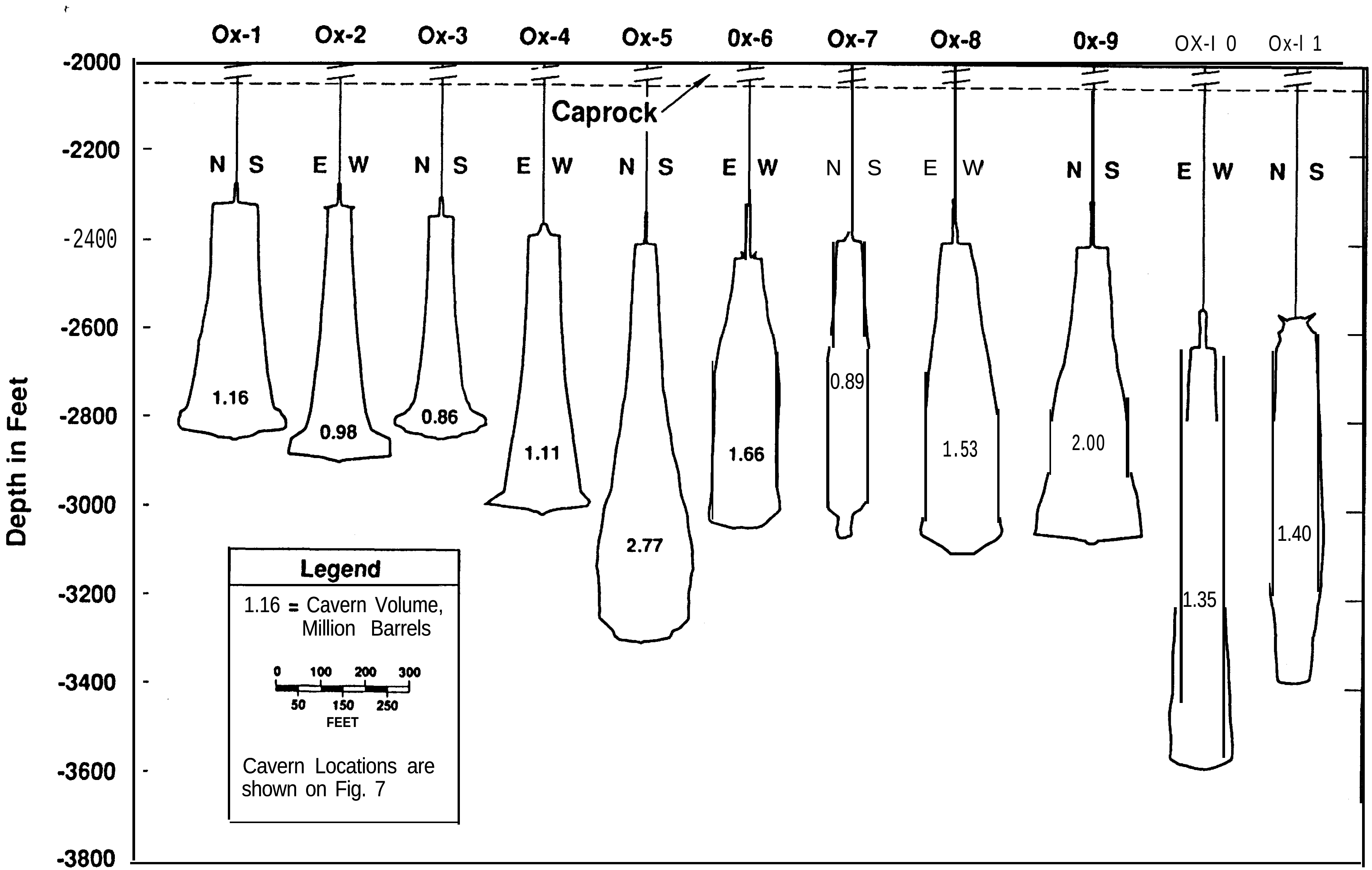


Figure 15 **Oxy** USA Cavern Depths and Configurations; Composite section, **not** a **cross** section.

Subsidence

Subsidence potential was discussed in the 1980 site characterization report and acknowledged to be a concern. The principal causes of subsidence were identified as fluid withdrawal of water, gas, and oil, cavern collapse, and cavern creep closure.

Ten years of experience and numerous observations can now put these and other subsidence sources into accurate perspective, and provide numerical bounds on each. The principal sources and average values, a order of imnortance, are:

Subsidence Category	ft/vr
a) cavern creep closure	-0.20
b) fluid withdrawal, Black Lake)	-0.08 (?)
c) regional subsidence	0.010
d) sea level rise	0.0075
e) other subsidence/collapse	minor
f) cavern collapse	none at W. H.

Understanding these sources makes it possible to estimate future elevation trends, and to enable remedial measures to be planned, where appropriate. Examinatior - the values shows that subsidence induced by cavern creep closure OVE :S the overall numerical budget, almost to the point of negating th -r sources. However, each is discussed briefly, in reverse orde. importance, to show how it affects the SPR site:

Cavern collanse (f) has occurred over numerous solution-mined caverns in Texas and Louisiana, generally resulting from uncontrolled brining and erosion into the overlying caprock and/or overburden [Refs. 11, 121. Hindsight in each case usually reveals the circumstances that led to failure.

Even though today's solution mining technology can avoid the problems that previously plagued the industry, West Hackberry has some older caverns adjacent to the SPR property about which little is known, and some potential for instability may exist. Abandoned Olin Caverns 1, 2, 3, 4, and 5 have not been sonar-logged and the internal dimensions are uncertain. 1989 volume estimates (Ref. 131 based on Olin production statistics showed the following values:

Olin # 1 & 2 - 147.7' dia x 600' ht; 1.83 MMB vol. (each)
Olin # 3 & 4 - 179.8' dia x 600' ht; 2.71 MMB vol. (each)
Olin # 5 - 80.2' dia x 600' ht; 0.54 MMB vol.

These dimensions are the cylindrical forms of known cavern heights (constructed diameters), using the assumed maximum volumes based on conservative estimates of production obtained from Olin Corporation [Ref. 14). The maximum cavern diameters are assumed to be wider; it is known, for example, that Caverns 1,2 and 3,4 are coalesced [Ref. 11.

One conclusion based on the above estimates was that the map (Fig. 6.12) in the 1980 report probably showed the cavern extents to be somewhat larger in maximum diameter than actually exists. No doubt the early estimates were conservative intentionally and probably based on history, as revealed in the ultrawide former Olin Caverns 6 and 9. Although Olin Caverns 1-5 have apparently been stable for some 40 yrs, uncertainty remains.

Other subsidence/collanse (e) resulting from mining of salt or sulphur has occurred at numerous other domes in Texas and Louisiana, but mining is absent at West Hackberry. However, cracking of the SPR brine pond liner in 1987-1988 may be related to local subsidence caused by cation exchange reactions in the underlying clayey soils, upon interaction with the brine in ground water [Ref. 151. This latter aspect is discussed further under Environmental Considerations.

Sea Level Rise (d) is occuring in the Gulf of Mexico at a rate nearly double the global rate. The mean rise in the Gulf is 0.23 cm/yr (0.0075 ft/yr), an almost insignificant amount in comparison with that caused by subsidence. Rise in sea level, although not strictly subsidence, has the same effect as negative motion landward, i.e., subsidence. Increased global warming conceivably could accelerate the rate of future sea level rise.

Reeional Subsidence (c) is widespread in coastal Louisiana, owing to numerous factors which are difficult to quantify individually. Subsidence is often considered together with sea level rise [(d) above] and termed relative sea level rise [Ref. 161. The combined term is useful because they work together in influencing the ongoing loss of coastal wetlands in Louisiana. Because the West Hackberry site is in this zone, the predictive maps for the year 2033 are instructive (Appendix B). The worst case shows that only the higher part of West Hackberry island will be above open water at that time. These maps were developed without regard to localized subsidence caused by solution mining and oil extraction, making their predictive value all the more significant. The current regional subsidence rate for the Hackberry station, based on USACE tide gage readings and corrected for Gulf of Mexico sea level rise is 0.32 cm/yr. Relative sea level rise at the same station for the period 1942-83 is 0.55 cm (O.018ft)/yr.

Fluid withdrawal (b) is of interest at West Hackberry locally, because of the extensive production from the Black Lake oilfield. The subsidence resulting from those wells is of particular interest because of the known enlargement of Black Lake in the past 35 yrs, and the encroachment of the lake on the already low-lying land on the north perimeter of the SPR site.

Estimates of subsidence in the 1980 report [Ref. 1; p. 4-161 attributable to this source ranged from 3 to 5 ft from 1933-1978, a rate of 0.8 to 1.33 in/yr (-0.08 ft/yr). These estimates, if correct, may reflect additional sources other than hydrocarbon and water pumping from the oilfield because they are much higher than usually encountered in petroleum extraction. Alternatively, they may be in error; very little data is available upon which to make these estimates, and the oil companies claim to have none. The subsidence associated with fluid withdrawal under Black Lake may have little effect on subsidence on the DOE property, except perhaps locally along the northern portion adjacent to the lake.

Cavern creen closure (a) begins immediately upon the leaching of a cavern and will consume some 10% of the cavern volume over the projected 30 yr design life. Although greatest at the cavern bottom, where higher pressure and temperature contribute to more rapid creep, the closure occurs on all sides, including the cavern top and thus the overlying caprock and unconsolidated sediments exposed at the surface. A conceptual model of this process is shown in Appendix C, Fig. 2.

This process was understood in general terms at the outset of SPR, but accurate predictions of what would occur were not possible. Repetitive surveys of some 100 monuments have been made at West Hackberry over a period of seven years and the following conclusions are now possible:

1) West Hackberry has the largest average subsidence of any SPR site (0.205 ft/yr) [Ref. 173. The 1991 survey results show a lower rate, but survey errors are suspected in view of longer-term estasblished trends.

2) Cavern #115 has the largest value of single-point subsidence (0.27 ft/yr) of any in the SPR system [Ref. 171.

3) The greater rate at West Hackberry is attributable apparently to a combination of the greater creep rates observed in laboratory samples, and the somewhat deeper cavern depths (-400-500 ft deeper than Bryan Mound and Bayou Choctaw, for example) [Ref. 18 and Appendix C].

4) Projections of current subsidence trends show that the northern perimeter of the DOE property adjacent to Black Lake will be subject to perennial inundation within a very few years. The present mean-tide elevation of Black Lake is very nearly two feet, according to professional surveyor Gary Todd, Sulphur, LA. The estimated future elevations of the most vulnerable SPR locations are listed in Table 4 and Appendix C, Table 2 and are based on linear extrapolations of September 1988 and May 1991 survey values, respectively. Table 4 below is based on 32 months additional time averaging; consequently the data likely has somewhat greater validity.

Uncertainties involving these estimates remain; creep closure is most rapid immediately during and after cavern construction and this possibly could be manifested in reduced surface subsidence after some time.

TABLE 4: PROJECTED ELEVATIONS FOR SELECTED WEST HACKBERRY STATIONS
(in feet, relative to mean sea level)

f

STATION	Elevation (01183)	Elevation (05191)	Subsidence Rate (ftfmo)	PROJECTED ELEVATIONS, MIDYEAR 1995	2000	2005	2010	2015
SMS 3	3.51	2.787	0.00723	2.43	**1.99**	**1.55**	**1.12**	0.69
SMS 4	8.03	6.71 (7190)	0.01477	5.82	4.94	4.05	3.16	2.28
SMS 5	6.65	5.187	0.01463	4.46	3.58	2.70	**1.82**	0.94
wH6C*	6.28	4.825	0.01455	4.10	3.22	2.35	**1.48**	0.60
WH8A*	14.04	13.15 (9188)	0.01308	12.09	11.30	10.51	9.73	8.95
WH 108 *	8.02	7.259	0.00761	6.88	6.42	5.97	5.51	5.05
WH 110 *	7.98	6.239	0.01741	5.37	4.32	3.28	2.23	1.19
WHIII *	8.08	6.390	0.01690	5.54	4.53	3.52	2.50	**1.49**
WH 113 *	7.45	5.659	0.01791	4.76	3.69	2.61	**1.54**	0.47
WH114”	7.37	5.539	0.01831	4.62	3.52	2.43	1.33	0.23
WH 115 *	9.15	7.130	0.0202	6.12	4.91	3.67	2.48	**1.27**
WH 116 *	**8.01 (8183)**	6.442	0.01568	5.66	4.72	3.78	2.84	**1.89**

* Wellhead elevations are measured at some height above the ground surface; the ground surface adjacent to well pads is lower. Elevations in bold type are below mean tide level of Black Lake, – 2.0 ft.

However, this has not yet been observed in seven years of measurement; rate trends are completely linear. Also, further expansion of Black Lake seems assured, as fairly intensive hydrocarbon production continues, with concomitant associated subsidence.

In addition to vertical subsidence over caverns, some degree of horizontal movement is probably occurring, because both theory and observation elsewhere show that it occurs. Measurements of subsidence over sulphur mining have shown horizontal motion to be nearly a third of the vertical component [Ref. 191. Until such time that measurements are made, the amount of horizontal drift occurring at West Hackberry must remain speculative.

Hurricane Storm-Surge Levels

The 1981 site characterization report indicated 100-yr storm-surge flood levels that range between 4.5 and 6.5 ft above mean sea level, but also acknowledged that Corps of Engineers estimates for Sabine Lake (30 mi west) would project a 10.5 ft surge height as far inland as West Hackberry.

The 1985 revisions to Federal Emergency Management Agency (FEMA) flood insurance zones are reproduced in Figure 5, and reveal lOO-yr flood elevations that approach ten feet [Ref. 201. The FEMA maps incorporate probabilities of hurricane frequency and severity, and these flood elevations would only develop as a result of hurricane surges. The elevations given in the Cameron Parish Flood Insurance Study [Ref. 211 for lo- and loo-year floods are 4.2 and 8.7 ft, respectively; values for the 500-yr flood were not computed but could approach 12 ft, or even more. The new values are consistent with the Corps of Engineers estimates cited earlier. The newer estimates indicate that significant portions of the SPR site would be inundated, and also that there is little difference for the SOO-yr flood. These probability values are subject to change, especially if global warming increases, with concomitant increase in hurricane severity [Ref. 221. The hurricane surge predictions become more significant when considered in conjunction with ongoing cavern-induced subsidence, and with projected regional subsidence.

Seismicity

The 1980 site characterization report discussed the extremely low seismicity of the Gulf Coast region and indicated that small earthquakes might occur during the life of the West Hackberry facility. Such earthquakes probably would not result in any significant damage, either from shaking or ground rupture.

An earthquake of Richter Magnitude 3.8 occurred south of Lake Charles on Ott 16, 1983, with the epicenter 17 mi north of the SPR facility. Even though the felt intensity reached Modified Mercalli V (MM V) near the epicenter, the earthquake was most probably not even felt at the site, as the isoseismal map shows it to be in the MM I zone [Fig. 16; Ref. 231.

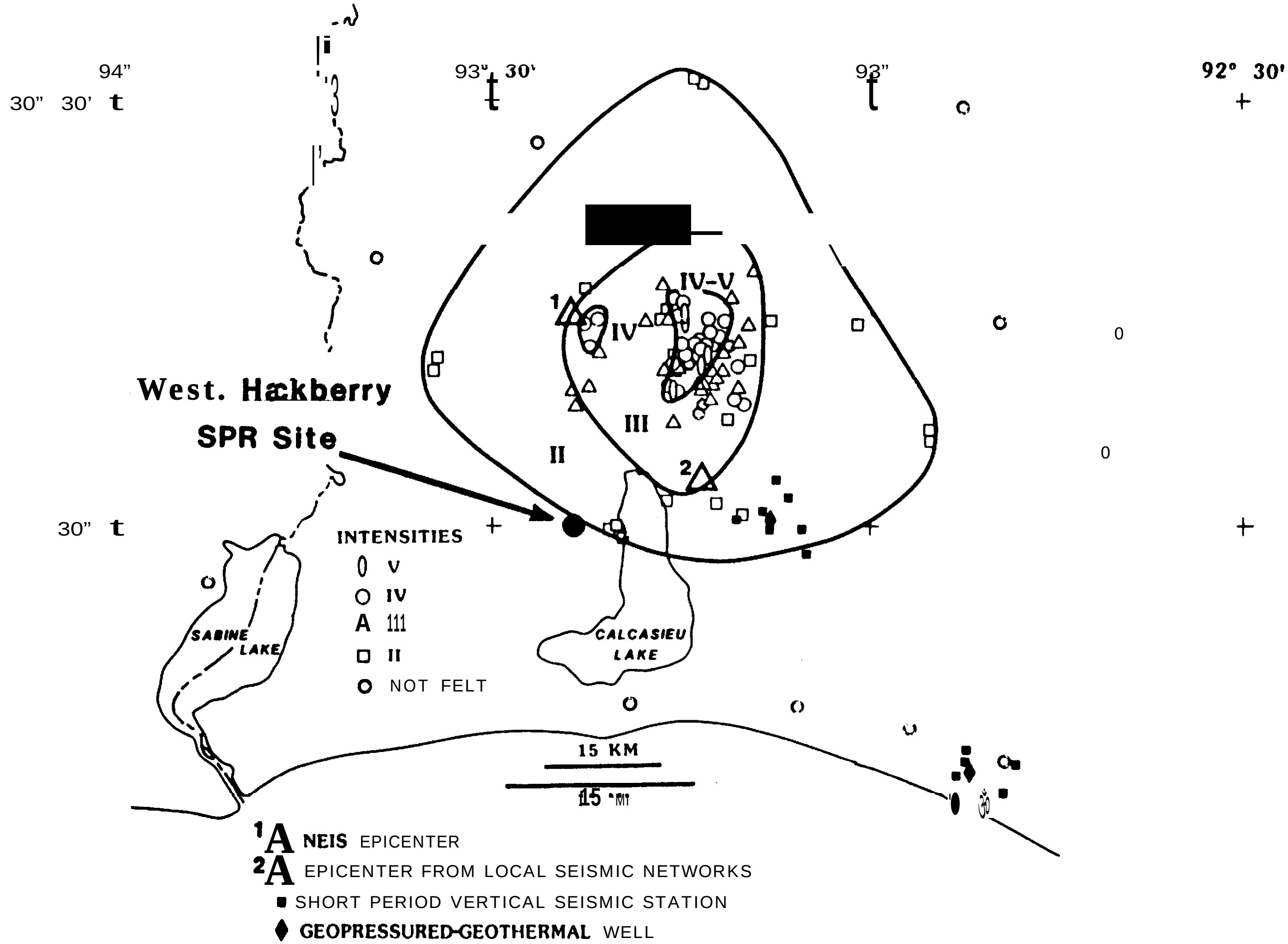


Figure 16 Isoseismal map, Lake Charles earthquake, 16 October 1983, magnitude 3.8, with stations used in location determination. [from Ref. 23]

Even near the epicenter, the maximum effects were a few instances of books falling from shelves and several unsubstantiated reports of cracked plaster, but generally only rattling of doors and dishes was noted.

The 1983 Lake Charles earthquake is instructive in explaining several aspects of Gulf Coast seismicity, and also in validating the seismic environment discussed in the 1980 site characterization report. Most geophysicists now agree that earthquakes of MM VI (slightly larger than the Lake Charles earthquake) can occur anvwhere along the Gulf Coast. Most likely these events originate in deep basement faults, or in combination with more shallow growth faults. Stevenson and Agnew [Ref. 23) proposed such a mechanism for the Lake Charles earthquake, with a focal depth of 14.04 km, possibly on a down-dip extension of the Lake Arthur growth fault system. Thus, deep normal faulting within the crystalline basement may control the configuration of many shallower Gulf Coast growth fault systems.

The largest historical earthquake (MM VI) occurred near Donaldsonville, LA, on October 19, 1930 and effectively approximates the design basis earthquake for the nuclear power industry in southeast Louisiana [Ref.24]. The Donaldsonville event produced an estimated maximum horizontal acceleration at the surface of -0.07 g. Such acceleration would result largely from higher frequency body-wave motion and likely would be of short (less than two seconds) duration. This does not present design difficulty even for conventional structures, such as SPR surface facilities, and would be of even less concern at subsurface cavern depths in solid salt within the dome because mine openings experience no damage at localities subject to surface accelerations up to about MM VIII [Ref. 251, which is greater than would be expected along the Gulf Coast. However, we? sing situated in fault zones could be problematic during fault Livation associated with earth temblors.

The nuclear industry LX further considered a New Madrid event (18110 12; RM 8+); peak acceleration at the range of West Hackberry would be even less than a repeat Donaldsonville event at the epicenter, and most probably not be felt. Also, several earthquakes have occurred with epicenters offshore in the Gulf with Richter magnitudes between 4.5 and 5.0 The largest not associated with a known geologic structure was RM 4.8. The conservative peak acceleration value of 0.1 g used by the nuclear power industry in south Louisiana is less than what is required in the design of hurricane-force wind loads, and the 0.1 g value represents an earthquake with more than a 90% probability of nonexceedance in 250 yrs [Fig. 171.

Environmental Considerations

A number of brine leaks and spills have occurred over the years, some as early as 1979, mostly in the vicinity of the brine ponds and brine pumps and there has been continuing concern that such leakage could enter fresh-water aquifers. In 1981, the monitoring well PB-1 was placed in operation east of the brine pond, being completed in a sandy zone between

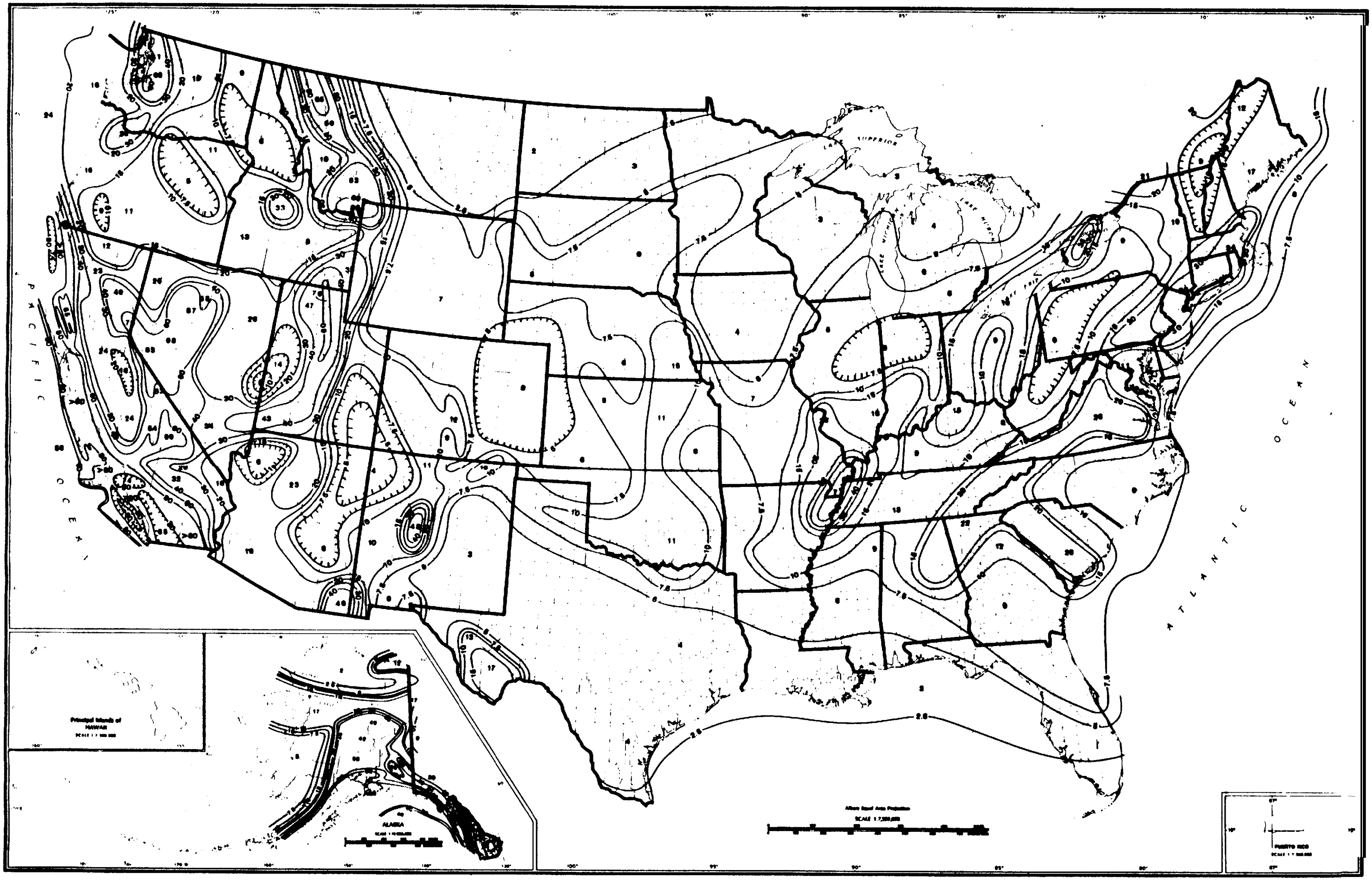


Figure 17 Mean horizontal acceleration in %G on rock, 90% probability of non-exceedance in 250 years. From U.S. Geological Survey MF-2120, 1990.

40 and 50 ft depth. Samples were collected periodically and showed salinity increasing from an initial 0.15 % to a range of 607% in 1988. Other conditions, such as cracking of the cement weight coat on the dike between the brine ponds, separation of the hypalon liner under the cement, and the location of Olin Cavern 4 (abandoned) along the east side of the brine pond caused added concern, as well as uncertainty about the cause of the increasing salinity.

Monitoring / remediation wells were installed around the brine pond system in 1988 (8 wells) and 1989 (2 wells). Pumps were installed in 3 wells, and continuous pumping was begun.

A major study was initiated in late 1989 with Geraghty and Miller Environmental Services and continued through 1990 [Ref. 151. They were tasked to determine the source and extent of the salinity in the groundwater, define the range of potential impacts, and recommend possible remedial measures. The study established what had been suspected -- that multiple sources were both possible and likely -- and that more detailed investigation would be required. Additional monitoring wells were installed, and numerous analyses made. Conclusions are tentative, but in general they discount prior Olin Cavern 4 as a major contributory source, and also the monitoring well PB-1 (even though damage and minor leaking led to its plugging and abandonment in June, 1989). Subsidence east of the brine pond was implicated as a possible cause, but little hard evidence exists to support this, other than a sloping piezometric surface.

The study clearly showed two zones of higher transmissivity -- a shallow zone some 20 ft thick near the surface, and a deeper zone separated by a confining layer of clay some 13 ft thick. There is apparent communication between the zones but the mechanisms are unclear. The analyses show substantially higher values of total dissolved solids in the upper aquifer, centered under and in the immediate vicinity of the brine ponds, and confirming that the brine ponds, brine pumps, and associated piping are the likely source.

In 1991 plans were under consideration to repair or replace the brine ponds, and to remediate the localized area of brine concentration by the pumping of 12 wells and the installation of additional wells.

SUMMARY OF SIGNIFICANT FEATURES AFFECTING SPR

No new discoveries have been made since the time of the original site characterization (1980) that would affect the basic integrity of existing underground storage at West Hackberry for either SPR or its neighbors, Olin Chemicals or Oxy USA, Inc. However, numerous refinements in the knowledge base have been made, in addition to some new well data and subsidence measurements. The revised information may impact SPR in the following ways:

(1) The substantially revised salt contours provide considerably more confidence with regard to dome configuration and structure, especially regarding dome edge to cavern thickness on the periphery.

(2) The location of perimeter faults, combined with gravity and seismic data, strongly suggest major zones (i.e., spines) of differential movement, separated by shear zones of anhydrite concentration. While there is no indication that such zones in the salt mass either are in contact with, or have affected existing caverns, their probable presence requires awareness. Very likely, such zones offset the more brittle caprock, and could affect surface facilities and/or well casings, as has occurred elsewhere. In addition, it is possible that caprock faulting causes localized pockets of subsidence. The delineation and characterization of these zones could be accomplished in future geophysical investigations and would probably be helpful.

(3) Subsidence at West Hackberry is occurring at a more rapid rate than any of the other SPR sites, exceeding an average of two inches per year over a network of some 100 stations. The maximum rate centers near Cavern WH 115 and exceeds three inches per year; this may be fault related, as indicated in conclusion (2) above. The already low elevation areas on the north side of the DOE property will most probably require mitigative action within 5-10 yrs to prevent perennial flooding.

(4) The environmental concerns associated with the intrusion of brine into shallow aquifers beneath the brine ponds does not appear to be directly related to geological conditions, although dispersion of brine in the aquifers follows the natural permeability of the subsurface units. The effect of the abandoned Olin Caverns 3/4 (coalesced) beneath the brine ponds is unknown, and could be contributing to a localized subsidence depression. Cavern 4 wellhead beneath the east dike might well be re-entered and the cavern sonared, if the brine ponds are repaired and out of service anyway. All of the early Olin caverns (#l-5) were plugged and abandoned prior to the advent of sonar survey technology; thus, their true dimensions are unknown.

(5) Injection wells for brine disposal are a reasonable backup, and possibly even a principal alternative, to disposal via brineline to the Gulf of Mexico. However, it is essential that appropriate horizons are selected, the wells are properly designed and constructed, and that continuing surveillance and maintenance practices are obsenred.

ACKNOWLEDGMENTS

We wish to thank the adjacent operators on the dome for their generous sharing of data and information, especially Jeff Spencer, Alan Levine, Bill Hart, and Paul Favret of Amoco Production Company, and Greg Trahan of Oxy USA, Inc. We also thank Ken Mills and Tom Eyermann of the Cavern Engineering group at Boeing Petroleum Services, and Brian Ehgartner and Chris Rautman of Sandia National Laboratories for their reviews of the manuscript.

REFERENCES

[l] Whiting, G. H. (1980) Strategic Petroleum Reserve (SPR): Geological Site Characterization Report, West Hackberry Salt Dome. Sandia National Laboratories Report SANDBO-7131, Albuquerque, NM.

[2] Serata, S. and X. Hiremath (1990) Cavern Design Technology in the 1990s and Beyond, Solution Mining Research Institute, Austin, TX, 22-25 April 1990.

[3] Bernard, H. A. and R. J. Leblanc (1965) Resume of the Quatemary Geology of the Northwestern Gulf of Mexico Province. a The Quatemary of the United States; Princeton Univ. Press, Princeton, NJ, p. 137-186.

141 Wyers, J. C. (1968) Natural Gases of North America, Vol. 2, p. 1950. Sulfur - Its Occurrence. Figure 1, Sulfur-bearing Domes, Gulf Coast Region.

[5] Dobbin,C. E. (1935) Geology of Natural Gas, Am. Assoc. Pet. Geol., p. 1069. Revised as Natural Gases of North America, V. 2, 1968, p. 1966.

[6] Ginn, R. (1991) Personal communication, and failure report of Oxy Chem. Inc., Railroad Commission of Texas, Austin, TX.

[7] Acres International Corporation (1987) Weeks Island Strategic Petroleum Reserve Geological Site Characterization Report. Sandia National Laboratories Contractor Report SAND87-7111, Albuquerque, NM.

[B] Magorian T. R. and J. T. Neal (1988) Strategic Petroleum Reserve (SPR) Additional Geological Site Characterization Studies, Big Hill Salt Dome, Texas. Sandia National Laboratories Report SANDBB-2267, Sept. 1988, Albuquerque, NM.

PI Bath, D. (1990) DOE/SPR Acquired Cavern History, Rev. 1. Boeing Petroleum Services Pub. No. D506-02634-09, New Orleans, LA,

[lo] Vrakas, J. (1991) DOE SPR Constructed Cavern History, Rev. 2. Boeing Petroleum Services Pub. No. D506-01644-09, New Orleans, LA.

[ll] Mullican, W. F. III (1988) Subsidence and Collapse at Texas Salt Domes. Texas Bur. Econ. Geol., Geol. Circ. 88-2,36 pp.

[12] Coates, G. IL, et al. (1981) Failure of Man-Made Cavities in Salt and Surface Subsidence Due to Sulphur Mining. Sandia National Laboratories Rept. SANDBl-7145, 136 pp.

[13] Division 6257 Internal Memorandum (1989) Olin Caverns 1 - 5 Volume Estimates, West Hackberry. Sandia Nat'l. Labs., 31 May 89.

[14] Olin Corporation (1989) Letter from D. P. Baham to J. K. Linn, Div. 6257, Sandia Nat'l. Labs., 30 Mar 89.

[15] Geraghty and Miller, Inc. (1991) Contamination Assessment Report / Remedial Alternatives Analysis, West Hackberry, Louisiana, Facility. Contract Report, Boeing Petroleum Services; G&M Project No IAlll.09, Apr 12, 1991.

(16) Penland, S. et al. (1989) Relative Sea Level Rise and Subsidence in tiuisiana and the Gulf of Mexico; Coastal Geol. Tech. Rept. No. 3, Louisiana Geol. Sunr., 65 pp.

[17] MeHenry, 3. M. (1989) SPR Annual Subsidence Report. Boeing Petroleum Services Rept. No. D506-02291-09, New Orleans, LA.

[18] Coin. K. L. and J. T. Neal (1988) Analysis of Surface Subsidence of the Strategic Petroleum Reserve Crude Oil Storage Sites from December 1982 to January 1988. Sandia National Laboratories Report SANDBB-1309, Albuquerque, NM, 39 pp.

[19] Deere, D. U. (1961) Subsidence Due to Mining · A Case History from the Gulf Coast Region of Texas. b Fourth Symposium on Rock Mechanics Proceedings, pp. 59-64.

[20] FEMA (1985) Flood Insurance Rate Map, Cameron Parish, Louisiana; Community Panel Nos. 225194 0075 and 0325, Rev. 17 Jul 85. Federal Emergency Management Agency.

1211 FEXA (1985) Flood Insurance Study, Cameron Parish, Louisiana. Federal Emergency Management Agency. Community No. 225194.

[22] Emanuel, K. A. (1988) Toward a General Theory of Hurricanes. Am. Scientist, V. 76, p 370-79.

[23] Stevenson, D. A., and 3. D. Agnew (1988) Lake Charles, Louisiana, Earthquake of 16 October 1983. Bull. Seism. Sot. Amer., V. 78, No. 4, pp. 1463-74, Aug. 1988.

[24] Gulf States Utilities Co. (1981) Geology and Geotechnical Engineering in River Bend FSAR: 18 Vol. Document submitted to the U. S. Nuclear Regulatory Commission; Vol. 3, Sec. 2.5.

[25] Pratt, 8. R., et al (1979) Earthquake Damage to Underground Facilities; Rapid Excavation and Tunneling Conf.; ASCE and Am. Inst. Min., Met. and Pet. Engr.; Atlanta, 18-21 June 79.

APPENDIX A

APPENDIXA

West Hackberry Regional Geologic History

Introduction

This overview is intended for those readers desiring general information, and for those with limited background in the geosciences. It is not detailed and is uneven in presentation by design. The reader who desires more complete information should refer ***to*** the original characterization report [Ref. 1, main report], or to more recent general references on Gulf Coast geology and tectonics [Ref. A-l].

Paleozoic Era (570-245 my)

Pangaea ("all lands"), the single protocontinent that drifted together at the end of the Paleozoic, resulted in a huge mountain mass, probably somewhat like the Himalayas today. It lay to the north (relative to todw! including the center of north America, and is thought to have been glaciated periodically, tying up much ocean water in icefields. No rocks of Paleozoic age are expected to underlie the site.

Mesozoic Era (245-66 mv)

The weight of this crustal mass melted the underlying mantle so that it broke apart, forming volcanic rifts and creating new ocean floor, similar to the African rift valleys and Red Sea today. The Gulf Coast Geosyncline was one of a string of rift basins created by the opening of the Atlantic in the breakup of Pangaea. This drifting apart of the present continents occurs at a more or less steady rate, as it has since the end of the Paleozoic.

Triassic Period: The initial deposits underlying the salt are oceanic basalts and red beds of Triassic age, called Eagle Mills in the Gulf Coast (Newark Series where better exposed on the East Coast). These deposits may extend out onto the new oceanic crust underlying the site.

Jurassic Period: The overlying redbeds of early Jurassic age are called Norphlet in the Gulf Coast. The original depositional basin of the Jurassic Louann salt and evaporites was one of the string of rift basins, similar to some evaporite basins in East Africa today.

The anhydrite overlying the Louann salt is called Buckner and the overlying dolomite is known as Smackover, the Gulf Coast correlative of the Arab limestone pay of the Persian Gulf, the most oil-productive horizon in the world. The remainder of the overlying Jurassic consists of a thick sequence of Cotton Valley limestone and bituminous shale. Although the salt in the West Hackberry dome is of Jurassic age, it may have been deposited to the north so that only oceanic basalts of this age or even Younger were ever deposited here.

The salt from which the West Hackberry salt ridge has formed is probably not in its original depositional position. It appears to have migrated southward and upward as a sill through the sediments described above or outside, seaward of the thick sediment wedge at a depth of two or three to six or seven miles. This sill is believed to be exposed at the toe of the sediment pile on the floor of the Sigsbee Deep (a trough in the Gulf of Mexico) today.

Continental rafting and seafloor spreading have revolutionized the concept of the origin of basins like the Gulf Coast Geosyncline; this concept of deep horizontal salt migration and intrusion is one of the most innovative and important ideas ***today*** affecting hydrocarbon exploration.

Cretaceous Period: The Cretaceous sequence of Hosston elastics and limes, Sligo oolites, Pine Island shale, James lime reef and Ferry Lake anhydrite, Glen Rose limes is overlain unconformably by the upper chalk section: Austin, Ozan or Annona, and Nacatoch or Arkadelphia with intervening Blossom or Tokio sands and thick shales. The shallow-water reef carbonates are equivalent to basinal shales to the south which probably underlie West Hackberry.

The chalk probably underlies the site in normal position, and may underlie the salt sill and thereby contain producibile oil and gas -- which DOE has acquired along with the salt.

Cenozoic Era (66-2 mv)

Tertiarv Period: The downdip surface section of the Gulf Coast proper in Louisiana and Texas is a thick pile of Tertiary sands and shales, correlative with the carbonates of Florida and the Bahamas. All of these deposits face the active east-west tectonic zone running from the Mexican volcanoes through the greater Antilles from Cuba to the Virgin Islands

Paleocene Enoch: The Tertiary sequence of the Gulf Coast starts with Midway shale, a normal marine deposit which preceeds the Laramide orogeny, the plate collision which created the Rocky Mountains and flooded the Gulf with coarse elastic debris. From our reconstruction of the regional geology, the ocean floor here was certainly solidified in place here by the end of the Cretaceous, so that it seems reasonably certain that a full, normal Tertiary section underlies the site.

Eocene Epoch: These are the oldest sediments deposited in the Gulf Coast delta sequence. As sediments accumulate on the north shore of the Gulf of Mexico, the older sediments are depressed and compacted, increasing their dip toward the Gulf. Ultimately, a thick sedimentary section accumulates on the edge of the continent, often referred to as a geosyncline. This simple regional picture is complicated by the instability of the underlying salt which forms domes such as West (and East) Hackberry.

Wilcox deltaic deposits as much as two miles thick, including coal measures which have been penetrated in adjoining Jefferson County, Texas, represent the Laramide deposits. These are overlain by downdip Yegua shales which in turn are overlain by Jackson shale. None of these deposits have been penetrated yet at West Hackberry.

Olieocene Enoch: The lowermost Oligocene Vicksburg shale is found in one well on the southwest flank of the dome. Hackberry dome is where geopressured shale was first encountered. A thick section of Hackberry deep-water shale overlies this Vicksburg occurrence and is unique to this dome, without any of the normal lower Oligocene sands found to the north. In all known cases, some 300 penetrations on the dome, this shale is at full lithostatic pressure. Table 1, the stratigraphic correlation chart, lists principal stratigraphic horizons important to the geological interpretation.

Hackberry Embayment: The West and East Hackberry Salt Domes form an east-west salt ridge in the middle of the Hackberry Embayment, the most prominent Frio feature-of the Gulf Coast. It is a large depression filled in Oligocene middle Frio time with deep-water shale. Big Hill dome, west of Port Arthur, Texas, and containing a previously-characterized SPR site, lies on the west edge of the embayment.

Three of the domes chosen for the Strategic Petroleum Reserve are in and around the Hackberry Embayment: Big Hill on the salt ridge forming the west edge; Sulphur Mines on an east-west ridge with Edgerly Dome near the north edge; and West Hackberry which is the type section of the Hackberry shale and lies in the middle of the embayment. Other similar embayments include the Nodosaria of older Frio age to the east, which includes the Bayou Choctaw dome, and the Houma of middle Miocene age, which is bounded by Chacahoula dome.

The Hackberry shale is an organic-rich unit in the Middle Frio (upper Oligocene), equivalent in age to Marginulina texana sands found outside the embayment. Turbidite sands near the mouth of the channels along the edge form isolated stratigraphic traps, some of the few in the Gulf Coast.

Nowhere as far south as this dome has this shale section been fully penetrated. Deep tests far out on the north flank show no more than 5 ft of sand as deep as 17,000 ft. Thus the entire lower and middle Frio sand section is missing here in the middle of the Hackberry embayment. There is a slight possibility that, although these sands have not yet been found, that some deep-water turbidites have penetrated the rim syncline and been included in the shale sheath.

This Hackberry shale is the shallowest geopressured shale known on any onshore dome, where it occurs above 3000 ft in the saddle between West and East Hackberry domes. The pressured Hackberry shale provides a sheath around the dome, forming a near-perfect seal. The top of this geologic unit is shown on the Hackberry Shale map (Figure 2, main body of report), the deepest horizon that can be mapped. The depth at the contact with the salt face is the shallowest that is protected by the shale sheath.

TABLE1 WEST HACKBERRY STRATIGRAPHIC CORRELATION CHART

	Unit	Symbol	Litholoq
	Recent: ***Beaumont clay***		peat, muck 6 mud
QUATERNARY	Pleistocene		
	Wisconsin		
	Alton/Peorian: ***Prairie Fm.***	a	sand and gravel
	Sangamon: ***Montgomery Fm.***	S	mud
	IllWoian	**i**	sand and gravel
	Yarmouthian: ***Bentley Fm.***	**(p)**	**mud**
	Kansan	**wks**	sand and gravel
	Aftonian: Williana ***Fm.***		mud
	Nebraskan	ne	sand and gravel
	Lafayette		gravel
TERTIARY	Pliocene	PL	silt, mud, and sand
	Miocene	MI	mud & sand
	Upper		
	Bigenerina f loridana	A	**sand and gravel**
			mud
		B	sand and gravel
			mud
	Textularia	L	marine sand
	Bigenerina nodosaria	2	deltaic sand
			mud
	Textularia stapperi	W	deltaic sand
			mud
	Middle		
	Bigenerina humblei	BH	unconformity
			shale
	Cristellaria	CI	thin sands
	Cibicides carstensi opima	***co***	sand
	Amphistegina	***AB***	shale
	Lower		
	Robulus	***RL***	marine sand
	Operculinoides	OP	bituminous limestone
	Cibicides	CA	sand and shale
	Marginulina ascensionensis	***MA***	sand
			shale
	Siphonina davisi	SD	thin sand
	- - - UNCONFORMITY - - -		
	Anahuac ***(Discorbis)***	***DR***	***shale***
	Oligocene		
	Heterostegina	H	coral reef
	Marginulina howei	***MH***	sand
			shale
	Frio	F	sands
	Cibicides hazzardi	CH	marine sands
	- - - UNCONFORMITY - - -		
	Hackberry facies	HB	geopressured shale
	Vicksburg	vx	black shale

Unconformity(s): A well-known angular unconformity occurs around the edges of the Hackberry Embayment. At Big Hill, for example, it extends production on the west flank of the dome. At West Hackberry it separates the geopressured shale from the overlying normal Frio sequence.

Frio Formation: Frio sands are the main producing unit penetrated near the dome, dipping at an average of 65 degrees near the salt face, some of the steepest dips found on the flanks of any salt dome. The deepest sand encountered is the Cibicides hazzardi (Table 1) , the lowermost of the upper Frio "regressive" sequence, approximately 100 ft thick. The sediments are thin laminated marine "fingers" deposited at the outermost or "distal" edge of sand deposition, at or near the edge of the continental shelf. They can but probably do not include any truly deepwater turbidite deposits because they contain a normal shallow-water fauna, at least primarily in normal stratigraphic position.

A marine shale and- sand-stringer sequence separates the Cibicides hazzardi sands from the main top Frio sands, some 200 ft thick.

Anahuac: The lower Anahuac marine shale separates both Frio pays from the overlying Marginulina howei sand, found on on the outer edges of the field. The Anahuac shale overlies the Frio, separating it from the Miocene sand pile. It is normally pressured and forms a seal for almost all of the oil accumulation against the salt.

The most dramatic angular unconformity on this dome lies at the top of the Anahuac. The Marginulina howei sand and underlying Frio sands were uplifted and eroded by salt movement before Miocene deposition. This basal Miocene unconformity is the largest in the geologic history of the dome. This erosion occurred in the interval in which Heterostegina coral reefs develop to the east, including the atoll surrounding Bayou Choctaw dome. The alluvial Miocene sands lie across dipping and eroded Oligocene Marginulina and Frio sands at angles as high as 65 degrees from the horizontal. Here the angular unconformity is underlain by geopressured shale sheath, on which the normally-pressured Cibicides hazzardi sands lie in angular unconformity

The top of the Anahuac shale is mapped (Figure 1, main body of report) like the Hackberry (Fig. 2, main body of report), to show the depth of additional impermeable units around the dome. This horizon is also best known from oil wells drilled on the flanks, so that these maps best reflect the control used in the subsurface study.

Miocene Epoch: The outer edge of the shelf grew southward past West Hackberry in lower Miocene time, so that the Anahuac shale is overlain by a sand pile. This sand pile being dumped off the south edge of the North American continent at least since the Miocene has deformed the underlying Jurassic salt into ridges and domes of which West Hackberry is one of the largest. Dips in these sands are limited to 35 degrees, even against the near-vertical salt face, except possibly at the west end of the dome. The base of the sand pile is paleontologically marked by the disappearance of Discorbis "restricted," the last far-offshore deposit in the stratigraphic sequence. The rest of the lower Miocene is represented by thick alluvial sands. The lower part has marine shale breaks including Siphonina davisi, correlated on some logs.

The middle Miocene is represented by the last marine shale breaks, particularly those containing the Amphistegina B fauna with volcanic ash from the Mexican orogeny. This is the shallowest paleontologic data point available around the dome. Table 1, the stratigraphic correlation chart, shows younger zones by their standard paleontological name, even though the marker microfossil is not found in the non-marine sediment at West Hackberry. These units have been correlated around the dome but have no other recognized name.

The upper Miocene alluvial sands are are all stacked point bars deposited by the Sabine and similar small rivers separated by silts. These thick, permeable sands are only partially mineralized close to the salt face. They do not represent a threat for oil leakage from the caverns which are not leached close to the edge of the salt.

Pliocene Eooch: The alluvial section continues through the Pliocene, with slightly more backswamp silt. The basal unit is a thick gravel corresponding to the Goliad of Texas. The apparent unconformity below this gravel is eroded deeply into the Miocene close to the dome, indicating the dome had extensive surface expression during this onshore alluvial deposition.

matemarv Period: Pleistocene Enoch;

The basal pre-glacial unconsolidated Lafayette gravel erodes into the underlying Pliocene. The overlying sediments were deposited during and after each of the glaciations of the continent to the north, when sea level was as much as 450 ft lower than today, and in the following interglacial stages as the sea returned to near its present level. Thus the basal sand of each sedimentary sequence, outwash brought down to the Gulf, is correlated with the glacial stage and the overlying mud with the following interglacial. Some or all of the glacial stage is actually represented by the basal unconformity below each channel sand [Ref. A-21. These sediments are occasionally called Willis in this part of the Gulf Coast.

Nebraskan Stage: The oldest glacial sequence is Nebraskan, found at the top of or just above the Lafayette gravel. The overlying Aftonian mud contains a distinctive volcanic ash marker like those of the middle Miocene, which has been tied to the volcanic or erogenic theory of glaciation.

Kansan Stage: The Kansan, where marine, is the Lenticulina sand, at a depth of some 1350 ft on the flanks of the dome. The Peorian, Yarmouth or Angulogenerina clay, which represents the long interglacial interval in the middle of the Pleistocene, is at a depth of 1100 ft on the flanks of the dome. It contains the uppermost glauconite marker in the sedimentary section, indicative along with the microfauna, of the most recent open marine sedimentation.

Illinoian Stage: Montgomery *or* Trimosina sands, at some 900 ft depth, were deposited during the following glaciation. Sangamon clay was deposited during the following interglacial interval.

Wisconsin Stage: The Prairie outwash sands of which the basal Alton, at a depth of 200 ft on top of the dome and 400 ft on the flanks, is the thickest and most massive, having been correlated over almost every onshore salt dome. At the surface to the north, they make up the plain which runs from Beaumont through Lake Charles to Lafayette.

The sands **were** formed at the lower sea level which occurring when the continental icecap extended to the Ohio and Missouri Rivers, the main sediment sources for the Mississippi and the Gulf Coast. Most of them are thick alluvial point bars with basal gravels, although there is some beach sand in the sequence. More than 1600 ft of them are found in the canyon cut through Timbalier Bay just west of the Lafourche Delta. Away from the island (Hackberry) and the structural influence of the dome, these sands dip toward the Gulf at the rate of 20 ft per mile.

These unconsolidated sediments are found across the top of the dome, uplifted but not fully breached by the salt intrusion and its overlying residual caprock. The active faults inherent in the caprock extend upward as the salt continues to intrude, deforming these overlying sediments, all the way to the surface.

Recent Stage: Off Hackberry Island, The Pleistocene sands are overlain by Beaumont marine clay and mud deposited in the last 5000 yrs, during which time sea level rose some 450 ft as the earth's continental icecaps melted, leaving only the ice cover in Greenland and Antarctica. This clay was deposited in the marsh as a soft, highly-organic black gumbo. It includes peat and algal sapropels or greasy layers formed by nutrient blooms in the bays and lakes. Water content in these unconsolidated sediments is still as high as 70%. This clay is the seal for the oil accumulation in the caprock at Spindletop in Beaumont, which produced a billion barrels of black oil. Along with these Recent clays, peats, and algal sapropels are included minor river silts and beach sands; they are still nearly flat, with a dip toward the Gulf of only l-2 feet per mile.

There are a few thin beach sands formed on the chenier ridges like that at Cameron. The white beach sands are very fine-grained and well-sorted. This beach-ridge complex is a fan with intervening muds, gradually subsiding into the marine clay. The sands can shift dramatically during hurricanes, when waves break across the beach at Cameron and travel across Calcasieu Lake to break at Hackberry Island.

On the island, at the West Hackberry site, much of this clay has never been deposited. The postglacial sediments are much sandier and thinner than off the island -- in Black Lake for example, at the north edge of the site.

The active shallow faults originating in the caprock or salt shear zones have only displaced the Recent sediments a few feet. They do not pose any apparent risk to the storage caverns by themselves, but subsidence along them could conceivably damage surface facilities and well casings, as has occurred at other domes used for storage of LPG products, e* g. p Stratton Ridge, TX. [Ref. 6, main body of report].

References to Annendix A

[l] Worrall, D. M. and S. Snelson (1989) Evolution of the Northern Gulf of Mexico, with Emphasis on Cenozoic Growth Faulting and the Role of Salt. Chapt. 7, h The Geology of North America - An Overview; Geol. Sot. Amer., Boulder, CO, p. 97-138.

[2] Bernard, H. A. and R. J. Leblanc (1965) Resume of the Quatemary Geology of the Northwestern Gulf of Mexico Province. u The Quatemary of the United States; Princeton Univ. Press, Princeton, NJ, p. 137-186.

[3] GYM, R. (1991) Personal communication, and failure report of Oxy Chem. Inc., Railroad Commission of Texas, Austin, TX.

APPENDIX B

PROJECTED LOSS OF COASTAL MARSHLANDS

Louisiana

Coastal Louisiana, especially in the deltaic plain, has undergone continuing, progressive loss of its coastal wetlands in this century. The reasons are at once complex and variable, and generalizations to explain the loss often have been erroneous, at least in part. Scientists and engineers alike generally agree that all of the following processes affect coastal change [Refs. 1 & 21:

a) Sea level rise
b) Subsidence--some natural and some induced, from several sources, including sediment compaction, fluid withdrawal, and tectonic downwarping
c) Loss of annual flood nutrients and sediments from a now heavily modified and regulated Mississippi River
d) Death of vegetation from several causes
e) Canal/bayou construction
f) Possible increased major storm frequency
g) Muskrat and nutria "eat outs"
h) Increased erosion, influenced by all of the above

The combination of causes has led to an estimated loss rate that increased from 15 to 45 sq mi/yr. The U.S. Army Corps of Engineers, New Orleans District, estimates that about 31 sq mi/yr are currently being lost from the combined deltaic and Chenier plain, based on careful measurements gained from repetitive aerial surveys over many years [Ref. 31. The variation in rates are graphically shown in Fig. B-l, taken from Reference PI'

Numerous state and federal agencies have studied the problem because of the considerable impacts on this valuable economic and recreational resource. While some small variation in the rate and amount of estimated coastline loss results, none of the scientists disagree that it is occurring. It is obvious that massive amounts of concrete and fill cannot stop the process. At best, only local slowing has been effected, and engineered structures are often totally ineffective. Nonstructural techniques such as beach nourishment and vegetative stabilization have been more successful [Ref. 41.

Projections for 2033 show "best" and "worst" case scenarios (Figs. B-2, B-3), which incorporate several variable assumptions, and the data in Refs. 11, 2, &31. It is clear in looking at these maps that Chacahoula, Cote Blanche, Weeks Island, and West Hackberry sites will be affected ***eventually,*** even though there is uncertainty in the rate and amount of wetland loss. These maps are only estimates, and care should be taken to not use them in a "literal" sense; their revision is to begin in late 1991.

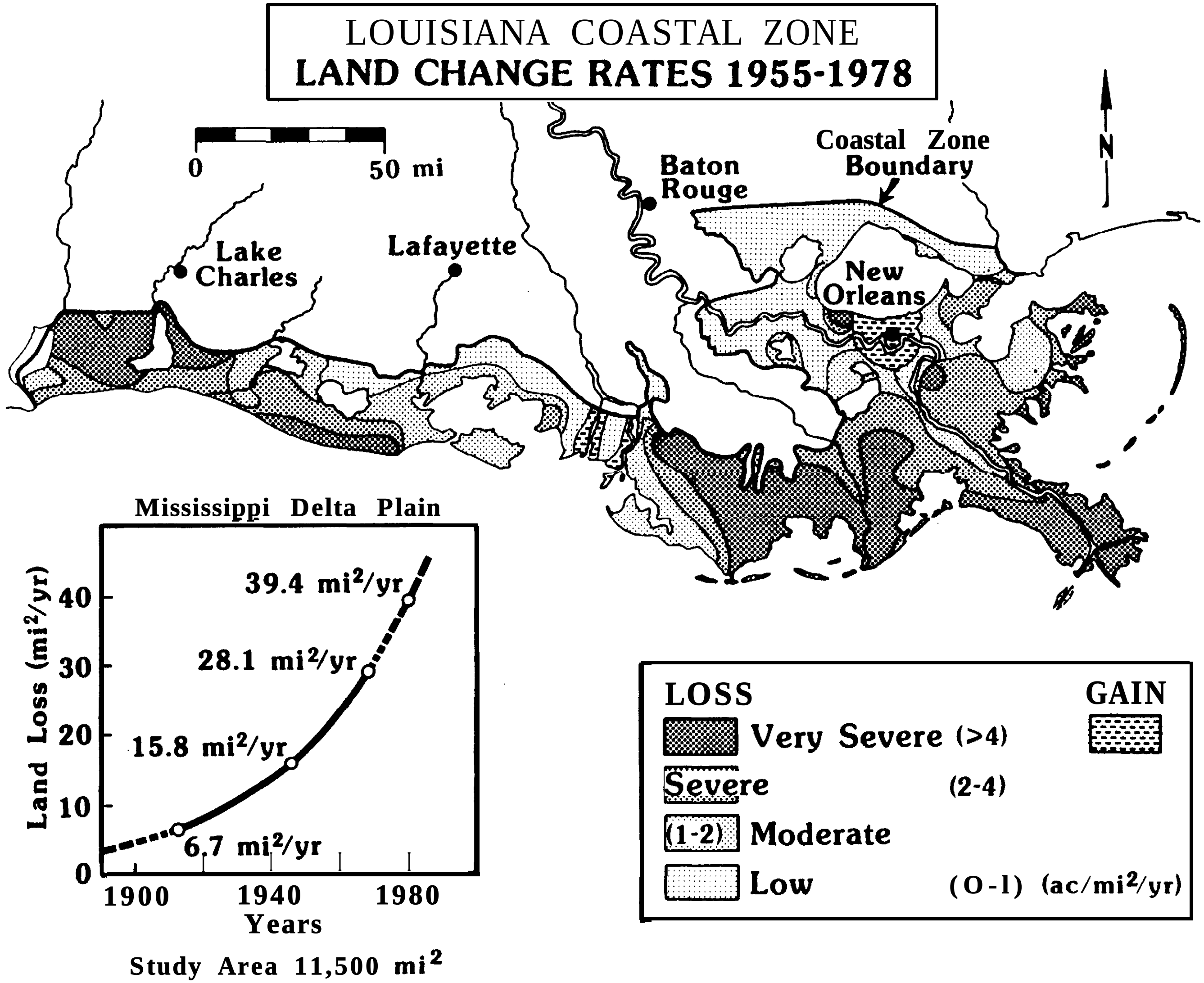


Figure B-l Distribution and rates of coastal land loss in Louisiana., 1955-78. Fig. 1 from Reference [2].

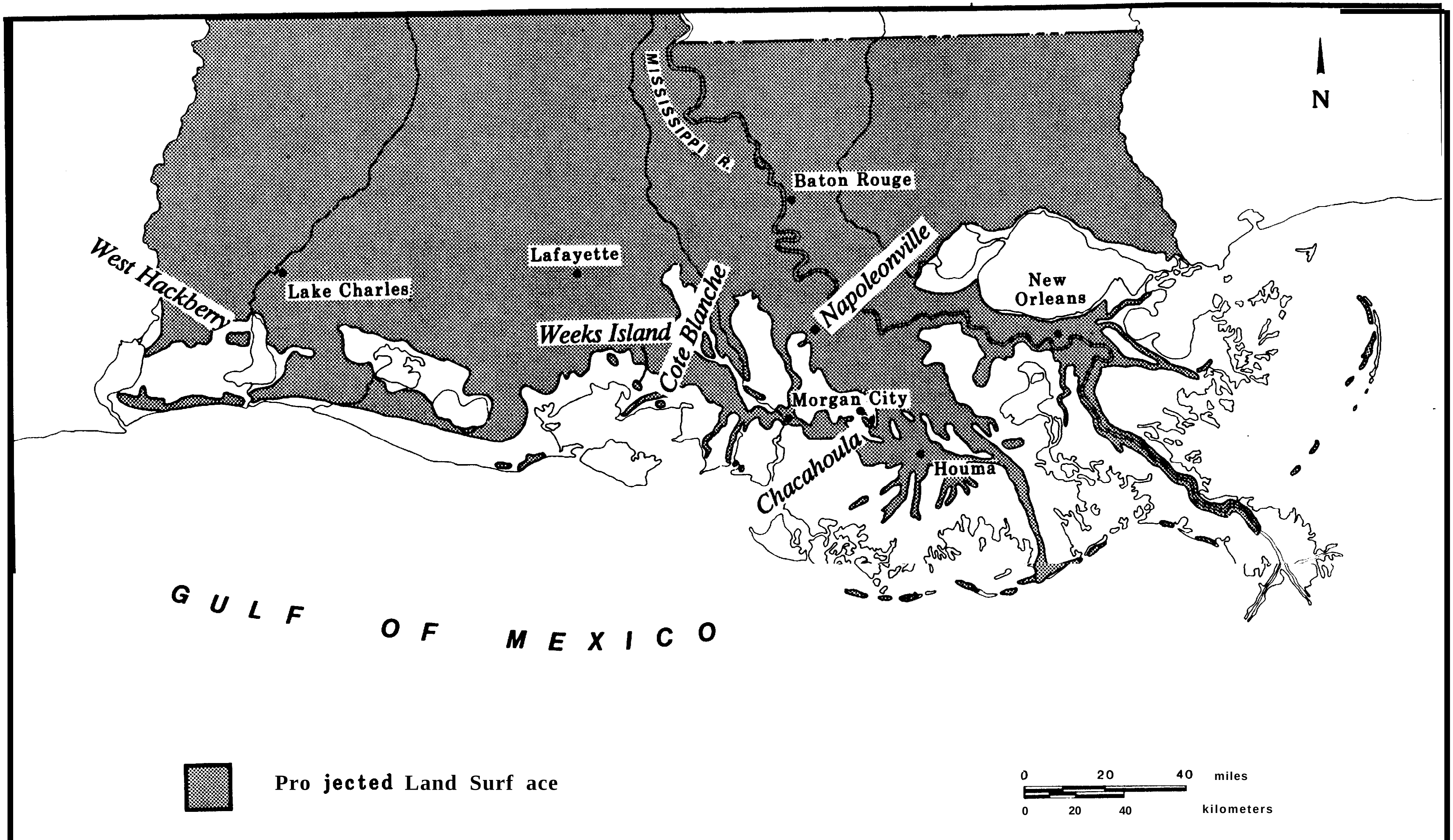


Figure B-2 **Projected Future Coastline of Louisiana for the Year 2033 (worst scenario)**

LOUISIANA GEOLOGICAL SURVEY

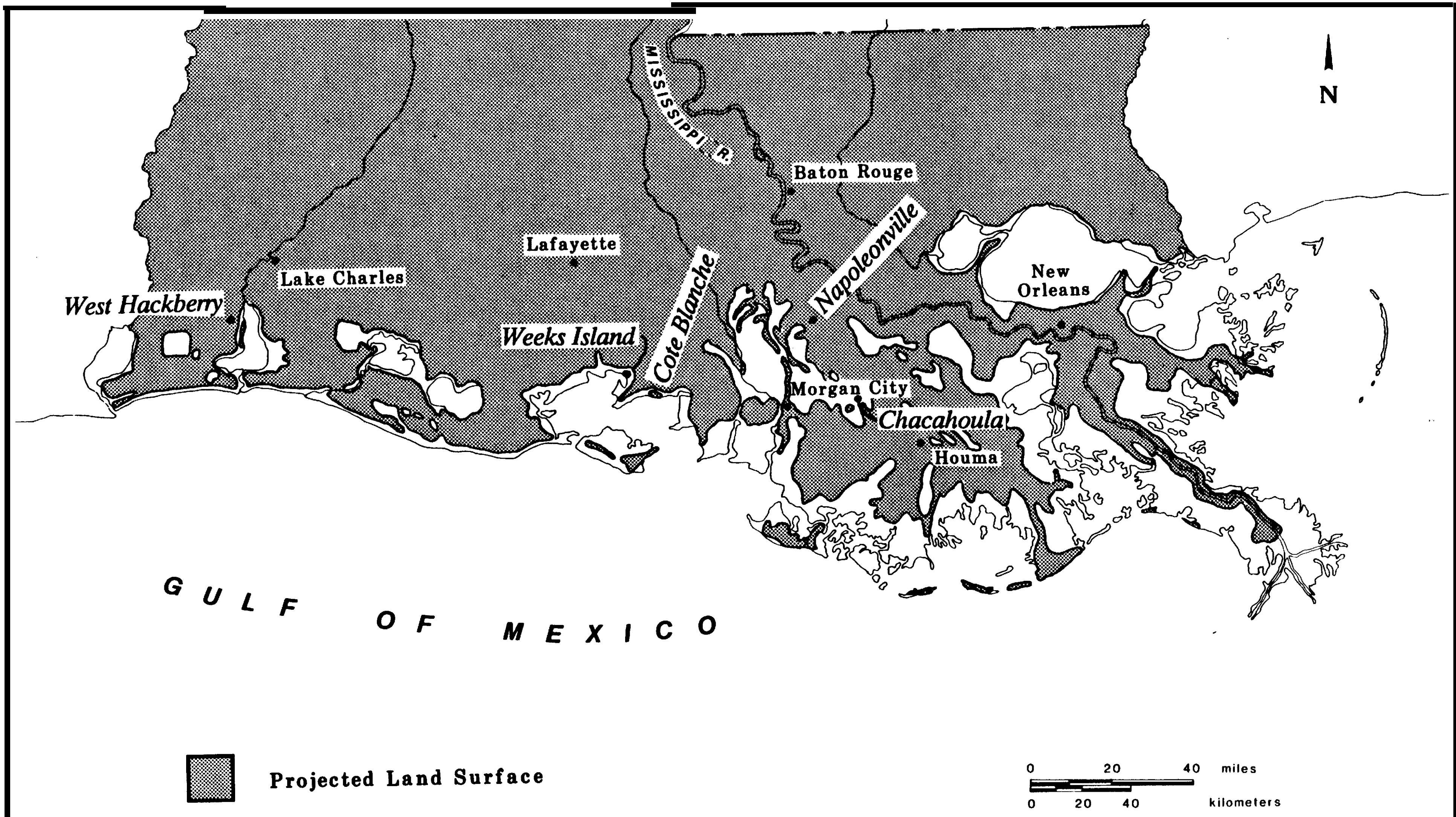


Figure B-3 Projected Future Coastline of Louisiana for the Year 2033 (best scenario)

LOUISIANA GEOLOGICAL SURVEY

Texas

The Texas coast does not experience anywhere near the rate of loss that Louisiana does [Refs. 5 & 61. Surface elevations, sediment types, and geologic conditions are generally more favorable with respect to coastal erosion than in Louisiana, but coastal retreat rates are apparently highest in Texas just west of Freeport. Measurements of coastal retreat by the Army Corps of Engineers [Ref. 71 near Sargent resulted in rates of 30 ft/yr, which would be about a kilometer per century. Subsidence rates in this vicinity are also very low. The Corps of Engineers is currently planning a massive concrete structure along some 10 miles of the Intracoastal Waterway in this vicinity, and has as its goal to preserve the integrity of all land north of the Intracoastal Waterway.

References to Annendix B

[l] Landscane DeveloDment and Coastal Wetland Losses in the Northern Gulf of Mexico. Amer. Zool., 30: p. 89-105 (1990), by R. Eugene Turner.

[2) Relative Sea Level Rise and Subsidence in Louisiana and the Gulf of Mexico. Coastal Geology Technical Report #3. Louisiana Geol. Sure., Baton Rouge (1989), by S. Penland, et al.

[3] Land Loss Rates: Mississinni River Deltaic Plain, Tech. Rept. GL-90-2. U.S. Army Engr. Waterways Experiment Station, Vicksburg, MI (1990), by L. D. Britsch and E. B. Kemp III.

141 Coastal Structures in Louisiana's Barataria Bieht, Coastal Geology Technical Report #l. Louisiana Geol. Sure. Baton Rouge (1985), by J. Mossa et al.

[S] Shoreline Pass to Brown Cedar Cut). An Analvsis of Hisotical Changes of the Texas Gulf Shoreline. Texas Bureau of Econ. Geol., Geol. Circ. 75-4 (1975), by R. A. Morton and M. J. Pieper.

[6] Shoreline and Vegetation-Line Movement. Texas Gulf Coast. 1987 to 1982. Texas Bureau of Econ. Geol., Geol. Circ . 89-l (1989), by J. G. Paine and R.A. Morton.

[7] I n f o r m a l of Eneineers. 22 Jan 1991.

APPENDIX C

Presented at 4th Intl. Symposium on
Land Subsidence, Houston, TX, 12-18 May **91.**
Intl. Assoc. Hydrological Sciences, Sponsor.

PREDICTION OF BUBBIDENCE RESULTING FROM CREEP CLOSURE OF SOLUTIONED-MINED CAVERNB IN BALT DOME8

JAMES T. NEAL
Underground Storage Technology Division 6257, Sandia National Laboratories, Albuquerque, NM 8712305800

ABSTRACT

The prediction of subsidence rates over a range of area1 configurations of solution-mined caverns in salt domes is possible, based on some fifty years of history in solution mining. Several approaches contribute to predictions: site-specific observations obtained from subsidence monitoring: numerical modeling, now becoming more practicable and credible: salt-creep data from testing: and rule-of-thumb methods, based on experience. All of these approaches contribute to understanding subsidence but none are totally reliable alone. The example of subsidence occurring at the Strategic Petroleum Reserve sites demonstrates several principles of cavern creep closure, the main cause of the subsidence, and shows that reliable projections of future subsidence are possible.

INTRODUCTION

Solution mining in salt is now a mature technology, having been practiced for more than 50 years, first in Europe and now extensively along the U. S. Gulf Coast. More than 500 permits for solution mining have been issued by the State of Texas alone, with the Barbers Hill dome at Mont Belvieu, Texas, having more than 100 caverns. Caverns are created as a result of dissolution during extraction of brine, and intentionally for storage of liquid or gaseous hydrocarbons, or other material such as industrial waste.

Frasch mining of sulphur from the caprock overlying salt domes is a type of solution mining, strictly speaking, and the accompanying subsidence and collapse effects are reasonably well known (Deere, 1961). The phenomenology associated with subsidence induced from sulphur extraction differs from that associated with the creep closure of caverns or mine openings in salt. However, subsidence associated with this type of sulphur mining it is not discussed here, but nonetheless is often concurrent with subsidence resulting from solution mining in salt.

Although common in occurrence, subsidence has not been widely reported on, possibly because of the perception of adverse publicity which most companies and institutions wish to avoid, and because of difficulty in obtaining accurate measurements. Subsidence is an acknowledged fact of life wherever large underground voids have been created, and openings in salt follow specific rules related to the rheologic behavior of salt. Some ten years of history of Strategic Petroleum Reserve (SPR) operations demonstrate subsidence phenomenology and point to means of prediction. Observations of subsidence from leveling surVeys, numerical modeling, lab creep testing, and rules-of-thumb have all been used to predict subsidence.

The 65 SPR caverns now contain some 500 million barrels (MMB) of crude oil in five salt domes [Fig. 1) and when full will contain about 675 MMB. An additional 73 MMB is contained in a former room and pillar mine at Weeks Island dome, LA, but the subsidence phenomenology there differs because of more shallow depth and much different geometry compared to solution-mined caverns.

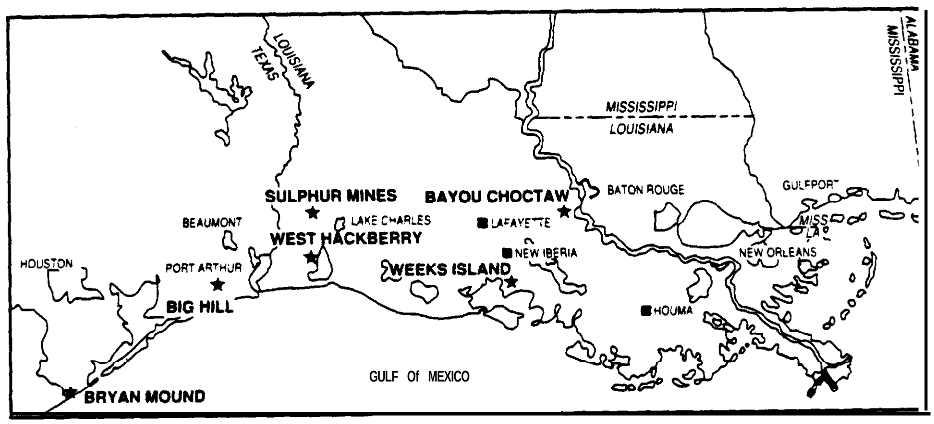


FIG. 1 The six Strategic Petroleum Reserve sites (star) are located in Louisiana and Texas.

ORIGIN OF CAVERN SUBBIDENCE IN BALT CREEP

The process of creep closure in underground caverns is understood qualitatively to occur radially into the cavern, with the largest amounts at the cavern bottom [Fig. 23. The closure requires the concomitant flowage of salt from all directions and therefore a gradual lowering of the surface, i.e. subsidence. Factors that influence the absented variations in creep closure in caverns are the constitutive properties of the salt, the depth, which controls temperature and lithostatic pressure, the differential pressure between that in the cavern and lithostatic pressure, cavern shape, and the configuration of multiple caverns.

Laboratory tests conducted at 320 C revealed large variations in salt creep response between sites and within a single site and may be due to experimental and/or constitutive differences (Nelson & Kelsall, 1984). Many authors believe that the data scatter between samples

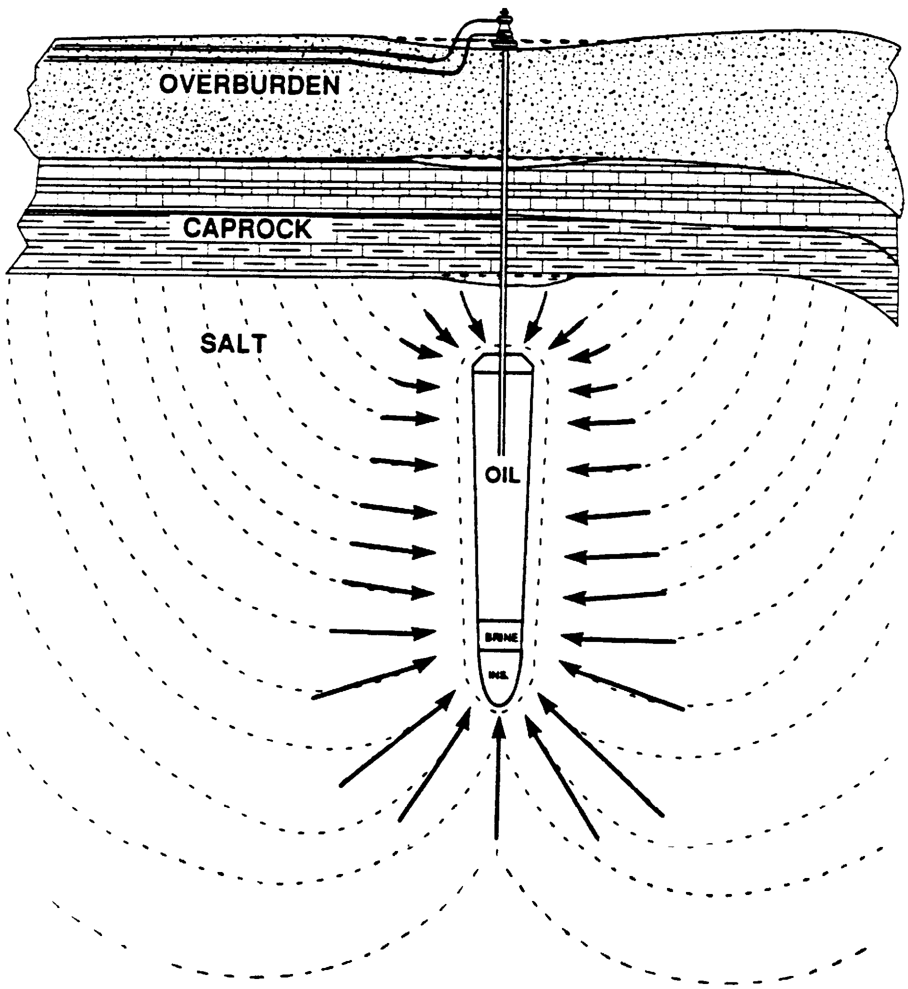


FIG. 2 Creep closure and subsidence associated with caverns in salt. Arrows show vector quantities of relative closure; dashed lines are flow patterns in salt. Some 10% of cavern volume is lost by this process in 30 years.

results from characteristics at the molecular level, as attempts to correlate impurities, fabric, or crystal size have been unsuccessful. Some samples show greater sensitivity than others to temperature change. Cavern shape influences creep by virtue of surface area and depth: an equal-volume sphere possesses about 61% of the area of a 10:l cylinder and consequently has less creep closure and more uniform pressure and temperature. Multiple cavern arrays display synergistic effects that result in additional subsidence over what would be expected for single caverns (Chow, 1974; Sutherland 61 Preece, 1986).

Observations in mines, boreholes, caverns, laboratory creep tests, and in calculations all show that salt under constant loading displays a rapid but transient initial strain response (primary creep), followed by a longer-term steady-state deformation (secondary creep), and **sometimes an** increasing rate of deformation leading to rupture (tertiary creep) [Fig. 33.

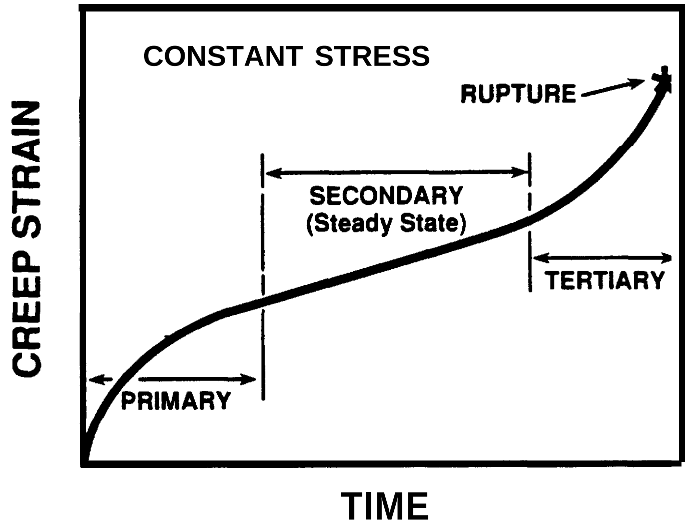


FIG. 3 Phases of creep deformation in salt.

OBBERVED BUBBIDENCE AT BPR BITE8

Subsidence observed at SPR includes multiplecaverns and sites and illustrates various principles of salt creep and associated subsidence, demonstrating varying salt properties, differing cavern shapes, depths and configurations, and variable site geology. Regional subsidence from other sources is also occurring in addition to that induced by the SPR caverns but this contributes only a small amount to the overall subsidence. Repetitive surveys at approximately annual intervals have been conducted at each of the SPR sites (Table l), showing values of average annual subsidence that ranged from 9 to 63 mm. A total of some 350 survey points include cavern wellheads, concrete foundations, and constructed monuments, all located over a total area of about 7 km2 . A wide range in values is observed both within and between sites; thus understanding the phenomenology is essential to establishing a predictive capability.

The data of Table 1 show a sevenfold variation between the smallest (Bryan Mound) and largest (West Hackberry) subsidence rates. Upon initial inspection basic parameters appear similar, but detailed examination reveals possible reasons for the variation. Laboratory creep rates of Bryan Mound salt are among the lowest of any salt studied (Wawersik & Zeuch, 1984), and the West Hackberry caverns are some 180 m deeper on average. While this may not seem significant, the exponential increase in creep with depth can account for the majority of creep occurring in the bottom 20% of the cavern [Figs. 2 & 41 (Todd, 1989; Heffelfinger, 1990).

TABLE 1 Summary of measured subsidence, SPR sites, 1982-88 (Goin and Neal, 1988)

8ITE (capacity, in Mm)	*WEST*	*WEEK8*	*BULPHUR*	BAYOU	BRYAN POUND
	[illegible]	[illegible]	-7%	[illegible]	(226)
AVO. subsidence (mm year-l)	**62.5**	**34.8**	*29.1*	**18.7**	9.0
Min./Max., **(mm year-1)**	**27/82**	**12/58**	**21/38**	**12/34**	**3/20**
Standard Error (mm year-1)	**3.14**	**4.02**	**3.84**	**1.83**	2.93
Cavern Depth,Pr top/bottom	**823/ 1372**	**140/ 226**	**823/ 1106**	**762/ 1220**	640/ 1250
8alt **Roof** Thickaos8,r	**186**	99	**375**	**670**	320
Caprock Thicknaar,m	**152**	0	**305**	**61**	99
Volume hrea-1 (MKBBL ha-l)	1.92	**0.64**	**1.46**	**1.24**	1.98
Other Activity	oil	salt: oil	sulphur; Oil	oil	sulphur
Extraction Ratio, t	-3	**-25**	W-M	---	-7

*Data from Weeks Island is included here, but storage is in a former room-and-pillar salt mine; Big Hill dome is not included, being now developed, and subsidence monitoring is just beginning.

Some of the data is not entirely consistent, and this difficulty has been attributed to inaccurate or shifting reference monuments, to instabilities in individual monuments, and possibly to leveling inaccuracy. Changes in survey practices, monuments, and reference points are expected to improve future measurements. The West Hackberry data are the most consistent, and this site has high interest within SPR because of the low surface elevation and location within coastal marshlands.

TREND FORECABT OF WEST HACKBERRY BUBBIDENCE

Projections of subsidence trends of the lower elevation areas of the West Hackberry site are shown in Table 2, based on rates established over some eight years of measurements. No indications of rate change were noted in any of the data, thus it is assumed to represent steady-state (secondary) creep primarily, with most of the primary creep closure [Fig. 3] having occurred early during the three-year leaching process to create the caverns. Thus the projections are linear, based entirely on observed rates. The projections allow for no change in regional subsidence or uplift rates, but this is only an insignificant small portion of the total subsidence measured. The results show that the already low areas of the site within a few years will be at or below the level of Black Lake on the northern perimeter, which has a mean tidal elevation of 0.6 m. These projections allow time to consider engineering solutions, e.g., diking.

TABLE 2 Projected Surface Elevations for Selected West Hackberry Stations in Meters, Relative to Mean Sea Level, based on 68 months data, 1982-88.

STATfOn		–m (9/88)	8UBSID1CBCB IUTB (mm mo.-)	l+2m	**Projected** a	Elavatioas 2009	2010	2015
SIs3	**0.162**	**0.909**	**2.38**	**0.72**	**0.b7**	**0.43**	**0.29**	**0.15**
SIqs 4	**0.320**	**2.13**	**4.71**	**1.75**	**1.47**	**1.18**	**0.90**	**0.62**
SI!xss	**0.329**	**1.70**	**4.84**	**1.31**	**1.02**	**0.73**	**0.44**	0.15
WIH 6C+	0.332	**1.58**	**4.89**	**1.18**	**0.89**	**0.60**	**0.30**	0.01
WIH 8A+	**0.271**	**4.01**	**3.99**	**3.69**	**3.45**	**3.21**	**2.97**	**2.73**
WIH 108*	**0.165**	**2.28**	**2.42**	**2.08**	1.94	1.79	1.65	1.50
WIH 110*	0.399	2.03	5.87	1.55	1.20	0.85	0.50	**0.14**
WI3 ill*	0.387	2.08	**5.69**	1.62	1.28	0.94	0.59	0.25
WIH 113+	**0.408**	**1.86**	**6.01**	**1.37**	1.01	0.65	**0.29**	-0.07
WIH 114*	**0.412**	**1.84**	**6.05**	**1.35**	**0.99**	**0.62**	**0.26**	-0.10
WIH 115*	0.466	2.32	6.86	1.76	1.35	0.94	0.53	0.12
WIH 116+	0.378	2.10	5.30	**1.67**	**1.35**	**l-03**	**0.71**	**0.40**

***** Wellhead elevations are measured at unknown height pbove the ground 81Jrface. Bold values are below mean tide level **of** Black Lake, 0.60 m.

Another mitigating measure would be to operate the caverns at the highest possible differential pressure (-90% of lithostatic at casing seat) to slow creep to the extent practicable. The effects of operating pressure on closure vs depth are shown dramatically in the calculations by Heffelfinger, 1990 [Fig. 43: operating at *lower* pressures could exacerbate existing subsidence.

NUMERICAL PREDICTION METHODS

Finite element modeling can be used to predict the creep of materials under loading and is commonly applied to engineering problems such as this. Segalman (1989) calculated creep closure and subsidence of a generic (average material properties and depth) West Hackberry cavern, using the JAC code (Biffle, 1984). Cavern volume loss rates are plotted along with subsidence volume and show close parallelism [Fig. 51. The ratio of subsidence volume to cavern volume loss is also plotted and shows that after 10 years some 70% of the closure will have manifested in subsidence, increasing only to 80% after 30 years, and showing the same steady-state trend. These calculations reveal volumes close to measured subsidence rates, and they appear useful primarily in explaining phenomenology at this point.

A more direct method of predicting cavern performance has been proposed by Thorns and Gehle (1983) in which the borehole that is constructed for the eventual cavern is observed over a period of several years and its measured closure rate is ratioed with the projected cavern dimensions. A limiting factor is that all measurements of closure are time dependent; thus long-term behavior can be estimated best when steady-state closure is indicated. Field tests are normally limited in duration, making it

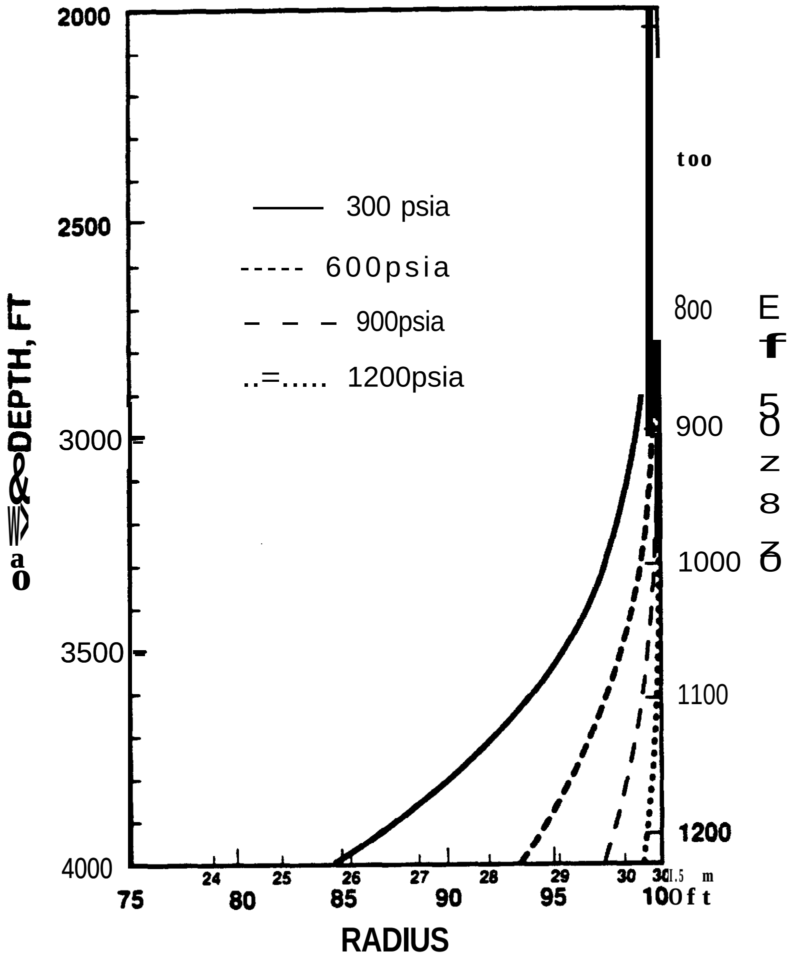
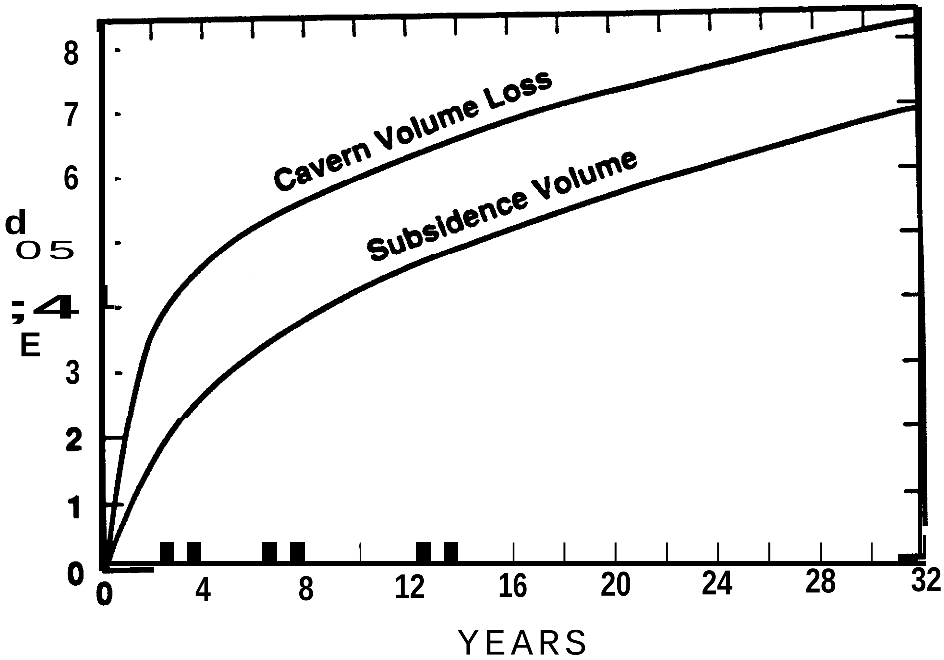


FIG. 4 Calculated effects of differential pressure at 600, 900, & 1200 psi (4.1, 6.1, 8.2 MPa), plotting cavern diameter vs depth at 30 years. From Heffelfinger, 1990.

difficult to obtain such information. However, long term projects that emplace multiple caverns offer excellent opportunities to use this method. Once the creep closure behavior is known, then subsidence estimates can follow, using other geologic information on caprock and overburden in conjunction. In this regard, similar experience and conditions are needed for extrapolation, unless modeling as described above is used.

SUBSIDENCE ESTIMATION

Frequently it is desirable to estimate subsidence effects in advance of actual cavern development, given the



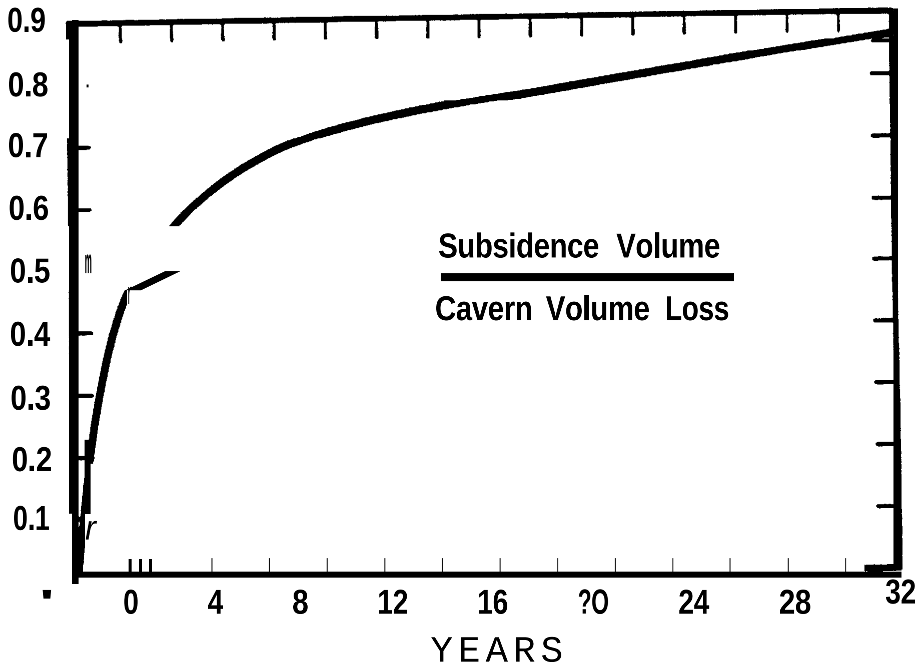


FIG. 5 TOP: Calculated creep closure and associated subsidence for a generic West Hackberry cavern. Initial rapid closure (primary creep) gives way to longer-term (secondary) creep. Bottom: Ratio of subsidence to cavern closure, showing some 80% of closure is manifested in subsidence in 30 years. From Segalman, 1989.

large investment in such operations. Approximations of the potential subsidence pattern was estimated for a 200 MMB generic cavern field [Fig. 63. The estimate of about 1.5 m maximum subsidence over 30 yrs is based on a rule-of-thumb for volume loss used in SPR (10% in 30 yrs), comparisons with domes having caverns at similar depths (Bayou Choctaw), similar group patterns observed in the

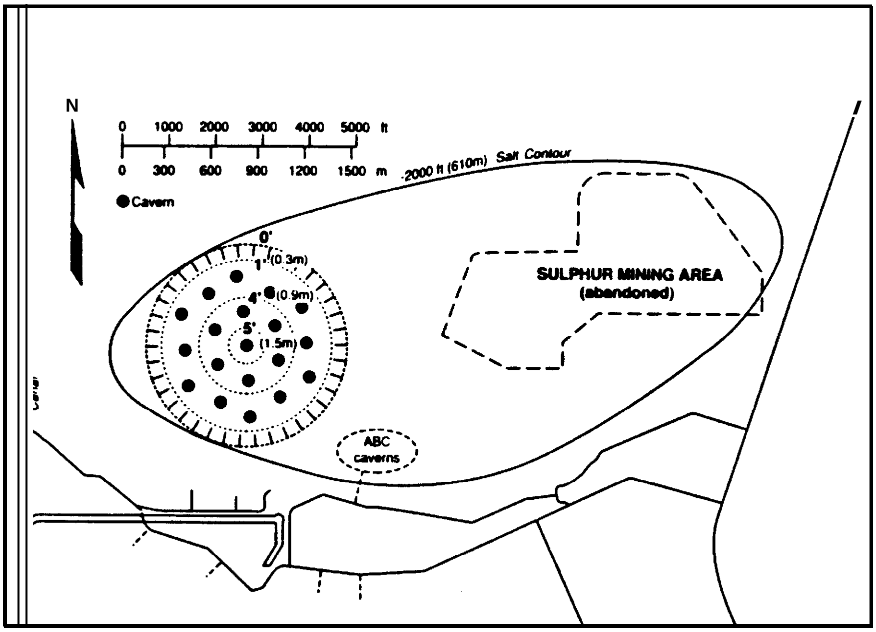


Fig. 6 Probable 30 yr subsidence pattern resulting from 200 MMB cavern field.

cavern field at West Hackberry dome, and knowledge of creep principles obtained from numerical calculations (Segalman, 1989; Heffelfinger, 1990) [Figs. 4 & 53. The estimate appears reasonable based on experience observed elsewhere, but there is no material property data or salt core to substantiate it.

ACKNOWLEDGMENTS Prepared by Sandia National Laboratories for the U. S. Department of Energy under Contract DE-AC04-76DP00789. I thank B. L. Ehgartner and G. S. Heffelfinger for their critical review and helpful suggestions in improving the manuscript.

REFERENCES

Biffle, J. H. (1984) JAC - A two-dimensional finite element computer program for the non-linear quasistatic response of solids with the conjugate gradient method. SAND8100998. Sandia Nat'l. Labs., Albuquerque, NM. Note: the users manual for JAC-3D is not formally documented.

Chow, R. (1974) Long term creep closure of solution cavity system. Proc. 4th Int. Symp. on Salt, 119-127, Northern Ohio Geol. Sot. Cleveland, OH.
Deere, D. U. (1961) Subsidence due to mining - a case history from the Gulf Coast region of Texas. Proc. 4th SymP= on Rock Mech. 59-64.
Goin, K. L. C Neal, J. T. (1988) Analysis of surface subsidence of the Strategic Petroleum Reserve crude oil storage sites from December 1982 to January 1988. SAND8801309, 39 pp. Sandia Nat'l. Labs., Albuq., NM.
Heffelfinger, G. S. (1990) Creep closure modelling of the U. S. DOE Strategic Petroleum Reserve caverns (abs). EOS, Trans. Am. Geophys. Un., 71, No. 17, p. 627.
Kelsall, P. C. 61 Nelson, J. W. (1983) Geologic and engineering characteristics of Gulf region salt domes applied to underground storage and mining. Proc. 6th Int. Symp. on Salt, vol. I, 519-544. Salt Institute, Alexandria, VA.
Nelson, J. W. & Kelsall, P. C. (1984) Prediction of long-term creep closure in salt. 25th Symp. on Rock Mech., preprint. Northwestern Univ., Evanston, IL.
Preece, D. S. f Sutherland, H. J. (1986) Physical and numerical simulations of fluid-filled cavities in a creeping material. SAND8600694, 40 pp. Sandia Nat'l. Labs., Albuquerque, NM.
Russell, J. E. (1980) A creep model for salt. Proc. 5th Int. Symp. on Salt, 349-353. Cleveland, OH.
Segalman, D. R. (1989) Informal communication of calculational results. Sandia Nat'l. Labs., Albuq., NM.
Thorns, R. L. t Gehle, R. M. (1983) Borehole tests to predict cavern performance. Proc. 6th Int. Symp. on Salt, vol. II, 27-33. Salt Inst., Alexandria, VA.
Todd, J. L. (1989) Informal communication of calculational results. Sandia Nat'l. Labs., Albuquerque, NM.
Wawersik, W. R. & Zeuch, D. H. (1984) Creep and creep modeling of three domal salts - a comprehensive update. SAND8400586, Sandia Nat'l. Labs., Albuquerque, NM.

APPENDIXD

SUMMARY OF WELLIBGS; WEST HACKBERRY SALT DOME*

WELL NAME

	0901	1501	1503	1506	1507	1510	1511	1512	1513	1513	1514	1515
REF. El.	21	1	13	20	20	20	20	22	20	20	23	21
SW8OL												
0		330										
s		370										
i		580										
P		940										
kS		1100										
ne		1220										
RP		1270										
PL		147aJ										
MI	2940	2880										
A	4380	3240										
8	5260	3480										
A8	7650	4330		6790	6120	7100	70SO	7050	6010	6010	5330	52SO
SD	9720											
DR	10020	5770	5590	8740	89A	9480	9300	94m	8960	8960	8810	8 1 8 0
		578OF?										
nn	11770			8930	9190	9950	9810	9940				
		57EiOF?			10010F300			10540F300				
F	12100	587OU				10550	10300					
CH		6420			10150	10950	10700	10760				
MB		6630			10520	11350		10860				
PR									9010	9010		
TO	12245	6700	6262	l am8	las40	11783	10930	10880	10297	10297		8347

WELL NAME

	1516	1517	1518	1519	1520	1521	1522	1523	1524	1526	1527	1528
REF. El.	21	22	21	23	20	21	15	20	22	18	19	20
SYWOL												
A8	5680	5520	5630	5720	4730			5410	5420	5650	5590	
DR		6480	6880	6130	5800							6260
TS						6050	5340					6470
TD	7000	6608		6250			5589	6563	660D	6500	6515	

* 1. See Table 1 for definition of stratigraphic abbreviations.

2. Suffixes to depths are abbreviations for:
   - U: Uncomformity
   - M: Mineralization
   - Pr: Overpressured
   - F : Fault - with throw in feet where estimated

3. First two digits of well designations indicate section number; second two digits indicate sequence number and designation on cross sections.

STRATEGIC PETROLEUM RESERVE
SLMARY OF UELL LOGS
WEST HACKBERRY SALT DOnE
****

WELL NAME

	1529	1530	1531	1533	1540	1541	1542	1543	1544	1H5	1546	1%7
REF. EL.	20	20	18	23	27	22	19	22	22	20	23	21
SYMBOL												
PL											1BDO	
											33&m	
AB			5050	5700	7050	5300	5500	5150	5300	WIO	5380	H1O
				622cm								
DR			6250	6550	9310		6450					
MH					9830							
F					10330							
CH					10720							
TS	5950	5no										
											6080M	6%m
ID	6050		6500	6700	1o900	6295		6250	6250	4%59	6169	6750

YELL RAMi

	15&a	1549	1550	1551	1552	1552~Jfl	15%	1602	1603	1604	16D5	1606
REF. EL.	21	21	20	20	20	20	27	23	20	24	10	20
SYMBOL												
MI									2580			
A									3200			
B									3800			
AB	mm	5290	5320		6950		7020	bmo	4070	5260		
SD								4870	4970	6560		
		55cm							5400M			
DR	6760	6150	6190		9240	9390	9110	5530	5730	7440	8410	9460
										8000M		
nn					10500	9940	9560		5820	8260		
f						10560	10110		6550	8780	9260	11020
									6720M			
Ctl						10970	10360		6840	9090	9580	11330
MB							10740		6900		9850	11500
TS				5840								
TD		6230	6256		10793	11006		6300	7250	9160	1oo80	

YELL RAMI

	1601)	1612	1614	1619	1621	1623	1625	1626	1628	1629	1630	1632
REF. EL.	10	22	10	10	10	10	21	21	16	10	10	10
SYMBOL												
a								480				
							1450u					
							267DU					
P								780				
ks								920				
M								1110				
RP								1220				
PL								1290	1450			
Ml		2270u							2470			
A		2850										
		332011										
B		3550										
		370DR										
AB		3920							4120			
SD							6220					
DR	7420		4640			57D0	7150		5800	7590	8470	
NH	8200						7830			7760		
									5060u			
F	8700								587D	8620	9150	
CH	8960								6290	8920	9830	
IIB									6450			
		4330F7										
		4450M										
TC								1930				
1s		4710		3359								
TD	9050		4785		5518	5990	7960	1970	7150	9080	10050	

WELL NAME

t l=~*t l=l lrr~lD**t~~==~*-*~*~~-~.~=*=~==*- n-l~-t lrrtnl*~~~~~8~~~~~~-~~~~~~x~8~x~~~~=-~n~x~%~8

	1634	1637	1638	1639	1640	1642	1643	1644	1645	1646	1647	1648
REF. EL.	10	29	30	29	29	27	20	30	28	30	20	27
sYwol												
PL		153al										
nr		277aJ										
A		3250										
AB		4100	5750		7040	5720		6230	7150	5800	4070	4830
SD		5810	6870			7070		7630	8450	7070	4970	6040
		5890u									541m	
DR	6670		7910	7860	9050	8ow	nso	aB70	9450	a070	5900	6990
A8							ES0					7070
							818DR					
WH	8230		8640	a530	10400	8800	8410	10D90	10530	8860		7640
F	8710		9120	9120	1087D	9240	8860	10560	11020	9420	6400	6310
											672oW	
CH	a920			9410		9SW			11290	9610	6840	8800
HB	9010					9690				9830	69W	
					11100PR							
							91WF150					
fD	9200	6500	9510	9600	112iW		9270	1072W	11650	998D	7250	9050

STRATEGIC PETROLEUM RESERVE
SLJMMARY OF WELL LOGS
WEST HACKBERRY SALT DOME
*****t**+**********************

WELL NAME

	1649	1650	1651	1661	1642	1663	1645	1670	1671	lTD1	1702	1703
REF. EL.	30	30	26	27	30	10	10	10	29	25	21	19
SrwBoc												
WI				2550								
A				3800								
B				4640								
AB	5220	5260	5330	7070	4780							
SD	6610	6570	6620		5880							
DR	7250	7530	7740	9300	6910	8000	8240		9080	5920	5880	5760
	825oN											
MH	W00	8160	8430	10500	7570	8850	8330		10360		6380	5660
							8870F450					
F	8800	8630	8830	10920	8050	9540	8980			6350		6490
CH	9150	8900	9180		8370	9840	9260			6920		
HB			9400			10190						
TS								5360				
TD	9350	9100		11240	8600	10630	9510		10966	7220	6700	7180

VELL NAME

	1704	1705	1706	1m7	17Q8	1709	1710	1711	1712	1715	1717	1720
REF. EL.	26	0	20	20	20	20	20	19	28	10	10	23
SYNBDL												
PL						2560						
MI					2750							
		2580U					252ou					
A		3100				3080	2910					
B		3300				3250	3210					
						3380F?	3550F?	405w	528aJ			
AB	3830	4600	3B1O	4650	4120	3900	3720	4180	5760			3710
SD	4930	5110	4050		4980	5050	4050		6970			4710
A8				5710								
DR	%20	5590	5390	5770	%W	5440	4380	5710	7720	7160	8150	5320
									7820F7			
RH					5920				64400	TIl0	9120	
F		5760	5710	6640					8930	8160	9570	6040
CH	5960	7030		7210		5820	4780		9300	8700	P010	6520
HB						5920	5300				10120	
TD	6500	7150	6000	6070		61W	5460	6300	9350	8764	10220	6800

WELL NAME

	1721	1722	1726	1728	1729	1730	1732	1737	173B	1742	1743	1744
REF. EL.	25	21	20	22	21	18	25	12	24	15	21	18
SYMBDL												
i	n o											
P	950											
Bp	12BD											
PL	1350											
MI	2450											
A	2830											
	3040M											
AB	3060	3780										
	3130M											
	3850M											
	4190U											
SD		4890										
DR	4690	5380	8250	7300	6140	6300	7510	7440	7190	5690	6380	6550
Aa						5760						
MH			9200		7200	66Bo	8290	8210	7940		7400	
					7340HW							
F		5650	9580	8430	7430	bozo	8920	8820	8520	6260		7380
CH	4930	6470		8960	8120	7600			8870	7500		
HB				9100	8210	7860				7900		
To	5340	6700	9800	9200	8400	7930	9290	9150		8200	8000	8200

WELL NAME

	1746	1747	1748	1749	1750	1751	1752	1753	1754	1755	1756	1757
REF. EL.	1	23	24	25	29	31	25	25	30	29	20	20
SYMBOL												
AB			4380	3880	5000	5120	4440	4370		4580	6490	5130
SD					5970	6200						6400
DR	5270	5320	5310	5470	6600	6750	5380	5250	7228	5860	8490	7480
MH		6050									9510	8060
F	5600	6560	5510	5770	7720	7840	5650	5380	8290	6440	9650	8540
CH	6370		6420	6900		8250		6220		6900		8800
HB	6490							6440				
										7180Pr		
TD		6810		7000	8020	8480	6190	6680	8900		10250	9050

WELL NAME

	1756	1759	1760	1761	1762	1763	1764	1765	1766	1767	1768	1769
REF. EL.	24	29	28	30	28	28	28	30	30	24	30	0
SYMBOL												
		4220U										
AB	4970	6610	4200	4690	5040	6330	4610		5110		6510	5930
SD	6170	8220										
DR	6910	8900	5930	6460	6890	8070	6230	6245	6740	8010	8180	
MH	7570	10400			7480	8890	6400		8010	8930	9220	7980
F	8130	10780	6750	7310	7920	9280	6850	6920		9320	9620	8370
CH	8520			8320		9500	7510	7740		9650	9890	8700
HB				8500								
TD	8630	10980	7300	a510	8710	9700	7980	7868	8420		10000	8780

WELL NAME

	1770	1771	1772	1773	1774	1775	1776	1777	1780	17al	1801	1602
REF. EL.	28	19	29	29	28	30	16	30	31	28	19	20
SYMBOL												
AS			4800		4720	5100	3780	5180	6920	4650	6510	5490
SD			6150		6260	6320		7120	8700			
DR	8330	4630	7ooo	7000	7170		5390	7910	8950	6000	8440	7180
												7820F260
MH	9230		7610	7465	7630			8700	10300		9170	8110
	9250F100											
F	9520		7850	8080	8100		5540	9180	10700	6960	9600	
CH	9870	4930	8300		8510		6330		10930	7410		
HB	9990	5770	8600									
											9840Pr	
TD	10060	5810	8700	8706	8780		6720	9550	11100	7680	9900	8490

WELL NAME

	1803	1804	1807	1808	1809	1810	1811	1812	1814	1816	1817	1818
REF. El.	20	20	20	22	20	22	18	19	17	20	20	20
SYMBOL												
AS	4890											
DR	7000	5890	7800	8370	8190	7880	7720	7430		7280	8300	8000
MH	7930		8670		9010	8920	8385	8245		7900		8650
							8760F600					
F	8370	6340	9180		9440	9230		8560	7480	8520	9390	9200
CH		6680				9400	8790		7950	8700	998s	9710
HB					9600	9540	8860			8790	10220	
TD	as40	6775	9453	9891	9734	9601	9100	8918	8173	8919	10336	9825

WELL NAME

	1820	1821	1824	1825	1826	1827	1828	1829	1830	1831	1832	1834
REF. EL.	20	22	10	26	30	28	29	29	27	28	29	20
SYMBOL												
AB						4570	4880	5580	5920	6540	4450	
DR	7590	6520	8480	5570	6290	6250	6810	7270	7390	8540	5810	7490
MH	8210	6870	9790		6450		7220	7990	7920	9310		7720
F	8790	7570	10170	6160	7025	7110	7770	8590	8410	9740	6300	8310
CH	9160	870	10490	6590	7540	7910					7020	8750
HB	9290		10610		7830							8890
TD	9451	8530	14010	6860		8110	8300	8650	8600	9970	7300	9000

STRATEGIC PETROLEUM RESERVE
SUMMARY DF WELL LOGS
WEST HACKBERRY SALT DOME
****

WELL NAME

	1841	1901	1901-ST1	1903	1904	1905	1906	1907	1909	1910	1911	1912
REF. EL.	32	29	29	1	1	21	21	23	13	21	21	21
SYMBOL												
a					350							
		3070M	3060M				3210M		2880M	3000M	2970M	2780M
			3310M				3810M			4270M	3540M	3240M
			3570M									
i				650	420							
			3310M									
			3570M									
P				900	660							
ks				1150	890							
ne					1240							
PL				1430u	1340U							
MI				247D	2510							
A				2820	2870							
B					3090							
AB				3930	4170							
				5220U	5360U							
A8											3760	
DR	6800	3650	4410	5880	5960			6000	3870		3980	4100
												4450M
A8										5020		4670
MH	7250		4600				5300		4250			
F	7900	4480	5170						4840		4240	
CH									5200		4900	
HB			5830									
TC						2460						
TS						3620						
TD	8600	5600	6040	6070	6260	4310	5480	6980	5440	5500	4950	5240

WELL NAME

	1913	1914	1915	1916	1917	1920	1921	1922	1924	1926	1928	1929
REF. EL.	19	20	22	20	21	10	1	10	21	10	10	23
SYMBOL												
	2800M	2730M	2590M	2720M	2650M							
			3250M		3020M							
			3960M		3240M							
			4350M									
A8			4490									
DR		2930	5650	6230	3330	7470	7430	7790	7300			
A8	4700	3240										
MH					3600	8000	8130		m o			
F					4210		8710	8530	8300			4440
CH									8560			5070
HB									a670			5610
TC										1730		
TS											2401	3200
BS												4350
TD	5550	4010	5800	6600	4350		8960	8810		1990		5950

STRATEGIC PETROLEUM RESERVE
SUMMARY OF WELL LOGS
WEST HACKBERRY SALT DOME

WELL NAME

	1931	1932	1933	1934	1934-ST1	1935	1936	1937	1938	1939	1940
REF. EL.	10	10	28	14	14	30	21	1	10	20	10
SYMBOL											
i				550							
			3110M			3060M				2570M	3470M
			3910M			3610M				2950M	
			4260M							3860M	
P				760							
ks				1020							
Bp				. 1240							
PL				1290				1310U			
MI				2370			2530U	2480U			
	2450M						3230M				
							3390M				
A				2740	2800			2620			
B				2850	2920			2950			
AB					4100	3620	4350	3400			
DR			4500				5420			4020	5280
A8			5250			5160					
						5700F?					
F							6080			4320	
CH							6550				
HB						5830					
				2880Pr				2910Pr			
TS	3620	2770		3320	4950			4900	4910	5100	
BS					4440						
TD	4300		5850	4500		6040	6800			5130	5850

WELL NAME

	1942	1942-ST1	2002	2003	2004	2005	2006	2008	2011	2013	2019	2029
REF. EL.	1	1	1	19	D	10	10	16	10	10	12	20
SYMBOL												
a				250			410	370				170
s				300			610	530				230
				450			720	680				420
P				630			1010	860				580
ks				860			1270	1200				780
ne				1100			1480	1490				1160
Bp				1200			1675					1390
PL				1390			1750					1480
DR	7180	7330										
MH		7720										
F	8040	8290										
TC				1640		1621	1890		2064		1620	1600
TS				2080	2080				2228		2030	2080
TD	8522	8730	5000	4600	2650	17%		1550		1775		1610

STRATEGIC PETROLEUM RESERVE
SUMMARY OF WELL LOGS
WEST HACKBERRY SALT DOME

WELL RARE

	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
REF. EL.	17	19	18	16	11	a	9	9	a	a	10	a
SYMBOL												
a	300		100	210	230	260	270		220	280		200
s			350	250	280	330				340	300	350
i	400	360	530	370	350	490	600	420	560	510	410	
P	600	720	720	600	550	730	850	720	760	710	690	
				710F100				840F50		880F?		
ks	880	940	930	720	740	910		950	890	960	850	
									920F50		930F200	
ne	1170	1200	1190	1020	1080	1180	1300	1290		1190	1150	1230
	1230F50											
Bp		1360	1400	1210	1250	1360	1450			1310	1330	1460
PL	1320	1450	1420U	1360	1380	1440U	1520	1410U		1470	1520	1635U
									1760U			
TC	1570	1600	1600	1630	1630	1710	1910	1620	1830	1680	1700	1770
TS	2090	2080	2080	2050	2070	2100	2010	2070	2140	2120	2100	2120
TD	2030							1720				1880

WELL NAME

	2042	2043	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054
REF. EL.	a	10	10	19	18	10	10	13	10	10	12	10
SYMBOL												
i	410											
P	750											
ks	930											
ne	1300											
Bp	1400											
PL	1480											
TC	1650			1590	1610							
TS	2170	2070	2020	2057	2020	1990	2010	1981	1980	2080	2000	2016
TD												

WELL NAME

	2055	20%	2057	2058	2059	2060	2061	2062	2063	2064	2101	2103
REF. EL.	5	10	10	10	10	5	10	10	10	10	0	16
SYMBOL												
a											130	170
s												230
i											340	320
P											480	500
ks											1190	940
ne											1520	1130
PL												1240U
TC	1580											1550
TS	1935	1970	1968	1919	1965	1919	2050	2040	2060	2042		
TD											1560	1600

STRATEGIC PETROLEUM RESERVE
SUMMARY OF WELL LOGS
WEST HACKBERRY SALT DOME

WELL NAME

	2104	2111	2119	2120	2121	2122	2130	2131	2132	2133	2134	2135
REF. EL.	a	20	9	5	10	15	10	10	15	10	10	10
SYMBOL												
•	350						350	335		355		
s	520		150				550	505		520		
	630		360	340	330	360	630	645		610		
P	860		530	500	430		860	1028				
ks	1200		1000	910	860	930	985	1260		1140		
ne	1420		1150	1180	1120	1170	1305			1220		
Bp					1250		1415					
PL	1530		1350U	1400	1360	1380U	1530			1330		
TC	1700	1551	1570		1700	1710	1670		1605	1560		
TS									2058	2049	2049	20%
TD	1710	1645	1590	1560		1740		1642	2258	2260		

WELL NAME

	2136	2137	2138	2201	2203	2207	2210	2222	2232	2249	22%	2258
REF. EL.	10	10	10	10	10	15	10	20	12	15	15	15
SYMBOL												
a					310		330					
s					560		590					
					650		710					
P					990		1020					
ks					1240		1260					
ne					1450		1610					
PL					1600		1720					
MI					2300	2290	2220				2380	2400
AB										2880		
SD							3060					
						2600M						2760M
DR					2890	2870				3770	3190	2820
MH									3970		4310	4320
F									4500	5410	4840	5010
CH									4880			5390
HB									5210			
PR					2890	2870						
TS	2062	2055	2048	2191				2000				
BS								2200				
TD					3613	34%	4033	4000	5425	5721	4910	5420

STRATEGIC PETROLEUM RESERVE
SUMMARY OF WELL LUGS
WEST HACKBERRY SALT DOME
****

WELL NAME

	2259	2264	2266	2267	2269	2271	2275	2276	2277	2278	2279	2280
REF. EL.	15	20	19	23	15	15	20	13	10	14	12	13
SYMBOL												
a		250										
	2250M				2570M							
	2400M				2950M							
s		410										
i		590										
P		940										
ks		1090										
ne		1320										
PL		1610										
MI								2620	2670		2330	2250
				2780M						2500M		
AB			2780M	2960	3020	4030	2800M			2670		
									2910M			
DR			3850	3980	3880		4260	2970	2960	3750	3200	3270
MH				4640	5065		5180	4290	4370	4760	4360	
F				5140	5650		3710	4760	4920	5350	4820	4260
CH							6000					4900
PR										3750		3270
TS		3290										
TD	2944	3424	3961	5198	5800	5820	6150	5015	5250	54%	5003	5150

WELL NAME

	2281	2282	2283	2284	2285	2286	2287	2288	2401	2402	2403	2404
REF. EL.	15	15	10	10	18	31	12	10	15	20	19	20
SYMBOL												
•				430		420						
s				520		530						
¥				660		580						
P				940		920						
ks			1170	1480		1360						
ne			1300	1660		1600						
PL			1500	1780		1730						
MI	2530	2730			2180		2650					
			2590M					2600M				
AB				2740				2680	6170	5690	5700	5980
DR	3140	3370	2750	3560	3050		3320	3740	8700	8430	8280	8340
								3780Pr				
MH	4230	5270		4930				4790	9470			9240
f	4730						5020		9950	9410	9250	
CH	4960								10100			
HB	5460								10300			
TC						1910						
TD		5515	3200	5501	3245	2000	5505	5326	10390	9622	9494	9388

WELL NAME

	2405	2406	2409	2410	2411	2412	2413	2414	2415	2418	2418-ST1	2431
REF. EL.	20	21	15	20	23	20	20	15	20	23	23	13
SYMBOL												
					3860M				3290M			
AB	6110	5670	5610	5890	6010	5840	5650	5860	6440	3450		5700
DR	8320	8060	8100	8450	8550	8340	8290	8150	8000	7630	7630	6870
MH	9040			9450		8955		8850	8650			7960
F		8480			9770	9410		9250	9090	8430	8440	8450
CH	9610	9030			10060		9895	9590				8970
HB	9820				10180	9650		9820				
TD	9965	9423	8838	9805	10410	9786	100%	9900	9300	8840	8910	9140

WELL NAME

	2432	2433	2435	2436	2440	2441	2442	2443	2444	2us	2446	2447
REF. EL.	15	15	20	22	23	29	28	27	25	15	17	15
SYMBOL												
•		270								270	270	
							2980M					
							3270M					
							3690M					
							4150M					
							5270M					
s		390								390	370	
i		450								450	450	
P		820								820	MO	
ks		1270								1270	1310	
ne		1690								1690	1620	
Bp											1720	
PL		1790								1790	1820	
AB	5310	5790	5300		5690	5780	5610	5560	5600	5790	4890	5410
DR	6870	6790	7310	8370	8230	8070	7040		6775	6790	7050	6710
MH	7920	7790		9250		8420		8800	7830	7790	8190	7580
F		8175		9770	8730	8900		9150		8175	8530	8160
CH	8820		8320			9390		9510			8920	8630
HB		8370								8370	9160	
TD	8900	8500	9215	10054	9250	9629	8385	9790	8540	8500	9500	8756

WELL NAME

	244a	2505	2507	2509	2519	2520	2521	2522	2702	2703	2705	2706
REF. EL.	10	24	15	20	20	22	23	19	20	10	10	10
SYMBOL												
a										340	340	340
s										580	580	580
i										690	690	680
P										970	880	1110
ks										1210	1370	1280
ne										1540	1590	1580
PL										1760	1740	1740
MI										2220	2310	2180
AB		6130	5710	5610		5390	5230	5220	5690			
DR		7690	6950	6950	6760	6545	6530	7020	8430	3400	3170	3115
MH		8990	8010		7725	7370	7390	8160				
F		9430	8550	8500	8270	7970	7830		9410			3400
CH			9130	9040	8720	8370	8270					
HB				9415		8570Pr						
											3330Pr	3450Pr
TS	9110											
TD		9674		9485	8901	8648		8430	9622	3457	3616	

STRATEGIC **PETROLEUM** RESERVE
SUMMARY OF **WELL LOGS**
WEST HACKBERRY SALT **DOME**
****

WELL NAME

	2707	2708	2709	2711	2712	2716	2718	2725	2727	2729	2737	2739
REF. EL.	10	10	6	13	15	10	10	10	10	10	10	10
SYMBOL												
•	330	330	340			320	330	330	330	330		
s	570	570	560		sao	570	S W	S W	sao	570		
*	700	680	690		700	670	675	710	700	660		
P	1040	1010	980		950	1000	1020	1020	1010	1000		
ks	1340	1360	1270		1350	1140	1390	1230	1240	1240		
ne	1500	1550	1490		1500	1430	1580	1470	1470	1480		
Bp			1590									
PL	1640	1650	1710		1660	1710	1730	1720	1710	1710		
MI		2480		2300	2260	2580	2270	2300	2310	2280		
AB											2450	3930
							3100Pr					
DR				3170	3110		3130				4020	5000
ml				42So							5130	6320
F				4800							6000	7040
HB								3280				
		3270Pr				2970Pr				3070Pr		
TD	3433	3473	3509	5223	3446	3369	3420	3420	3286	3320	6241	8050

WELL NAME

	2740	27U	2745	2746	2746-ST1	2747	2749	2751	2752	2752-ST1	2753	27%
REF. EL.	13	10	10	10	10	10	10	10	10	10	1	10
SYMBOL												
AB	3200	4990	4550	4540	4540	4600	4870	4780				4940
DR	4430	5860	5550	5460	5550	5520	5950	6040	6190	6070	6830	6480
		6830F450										
MH	6110											
F			6370		6050	5800	6610	6970	7640	7080	8400	8370
CH		6940			6430						9200	
HB		7130									9620	
						6020Pr						
TD	6800	7149	6764	6105	6503	6302	6995	7519	7783	7304	10824	8530

WELL NAME

	2755	2760	2761	2762	2763	2764	2765	2766	2767	2768	2770	2771
REF. EL.	10	11	12	12	13	13	12	22	12	10	13	16
SYMBOL												
MI									2270	2200		
AB	4150	4680	3410	3110	3140	3120	3530				3905	3940
DR	5370	5690	4700	4160	4290	4190	4800	3140	3120	3350	5070	5130
							5980F400					
F	7860	6230	6550		6170	6040		4180	4200			
CH	8350		6820	6060	6780		6130		4610			6240
HE	8590			6300	6890		6330	4830				
TD	8879	6460	6940	6328	7348	6301	6535	4914	4750		6876	6426

WELL NAME

	2772	2773	2774	2776	2801	2804	2807	2809	2810	2811	2814	2818
REF. EL.	16	10	14	12	15	a	12	16	16	14	11	13
SYMBOL												
a					330	U D	400	380			380	380
s					570	sao		560			S W	550
i					700	690		670			640	630
P					1090			950			930	900
ks					1360	1120	1140	1170			1100	1050
ne					1570	1460	1460	1305			1260	1290
PL					1700		1710	1480			1500	1470
MI	2330				2480	2740	2100		2310	2250		
AB		47So	4120	3550		3140						
DR	3440Pr	5630	5510	4830		3390	2970		3090	3030Pr		
MH			6460	5880								
F		5970		6250								
					3280Pr				3300Pr		2000Pr	
TC								1867			1960	2010
TD	3980	6134	7147	6545	3473	3441	3130		4409	4250	2050	

WELL NAME

	2821	2822	2624	2825	2826	2827	2828	2829	2830	2831	2851	2861
REF. EL.	1	12	12	12	10	10	10	17	10	12	10	1
SYMBOL												
a	330	330	340	400	320	380	340	365	370		400	400
s	560	590	570	S W	570	590	610	540	550			
i	640	670	660	670	680	650	630	620	600			
P	970	1000	950	950	960	890	860	900	890			
ks	1260	1270	1270	1250	1260	1160	1190	1170	11%			1130
ne	1520	1510	1510	1500	1560	1360	1480	1310	1350		1510	1380
	1660U											
PL		1710	1710	1700	1710	1470	1620	1420	1470		1760	1720
WI	2110	2270	2250	2210	2220						2770	2060
A0					2300					3530	3200	
DR	2640	3500	3170	2920						4930		3040
PR										4930		
TC						1920	1840	1710	1840			
M				2910								
TD	3230		3500	3520	3470					5885	3400	3100

WELL NAME

	2863	2867	2871	2880	2883	2889	2890	2891	2892	2893	2894	2895
REF. EL.	10	0	12	10	9	13	15	16	16	16	10	16
SYMBOL												
a				360	320	330				400	410	
s				550	560	560				570	590	
i				630	680	620				630	680	
P				750	970	900				900		
ks			1130	1155	1340	1160				1130		
ne			1470	1300	1600	1330				1280		
PL			1700	1505		1500				1380		
MI	2230		2030		2170		2400	2200	2205			2190
AB			2370									
	2800M											3150Pr
DR	2920		2630		2990		3250Pr	3210Pr	3360Pr			3200
TC				1950		1900				1807		
TD	3000		3300		3370	2094	3303	4020	4735	1878		4638

STRATEGIC PETROLEUM RESERVE
SUMMARY OF WELL LOGS
WEST HACKBERRY SALT DOME
****

WELL NAME

	2896	2897	2898	2901	2902	2903	2904	2905	2907	2908	2909	2910
REF. EL.	11	10	10	10	10	10	10	10	7	6	10	10
SYMBOL												
a	300						370	370	350	375	3%	280
s	570						540	540	570	570	550	
i	670						640	640	640	690	630	
P	1020				950		950	930	960	950	1045	
ks	1260				1210		1180	1180	1160	11%	1185	1110
ne	1550				1370		1340	1340	1350	1320	1300	1400
PL	1710				1620		1570	1640	1660	1625	1380	1510
MI	2190			2480	2250		21%	2240	2200	2150	1935	
						224W						
B						2670						
SD											2420	
DR	3150			2870	2910	2720Pr	2780	2690	2820	2690		
				2900Pr								
TS		2055	2056			3200	3125	3200	3200	3050		
TD	3500			3891							2722	1900

WELL NAME

	2911	2912	2913	2914	2922	2930	2931	2932	3001	3003	3009	3012
REF. EL.	10	10	12	10	9	7	10	6	10	10	10	10
SYMBOL												
a			350	350	370	240		370				
s			530	520	560	410		570				
i			620	SW	650	500		680				
P			980	860	940	860		950				
ks			1170	1150	1140			1120				
ne			1280	1260	1350			1330				
PL			1380	1380	1600			1630				
MI			1720		2440			2150				
											2520U	2550U
B												29S0
									4900M	4490M	4820M	4490M
												4770M
AB									4920	4790		4780
SD											5520	
DR			2360		2670			2680	6170	5950	5780	5990
						2070U			6520U			
MH									6670			
F										6440	6200	6500
CH										6700	6550	
HB										6860	6700	
VX										7034	6900	
					2820Pr							
TC				la30								
TS	2068	2500				3500	2085					
TD			2413		3004	3574		2830	7313	7055	6913	6632

STRATEGIC PETROLEUM RESERVE
SUMMARY OF WELL LOGS
WEST HACKBERRY SALT DOME
****

WELL NAME

	3014	3022	3036	3042	3050	3051	3052	3053	3054	3055	3103
REF. EL.	10	10	14	10	10	20	21	16	20	18	15
SYMBOL											
a									480		600
i									770		
P									920		
ks									1230		
ne									1460		
Bp									1560		
PL									1640		
									4940M		
B											3050
											5830M
	4960M						4850M		5120M	5420M	6130M
AB	4970		3850			5270	5050	4510	5130	5510	
							5200M	4700M	6100M	6140M	
							5550M	5150M		6550M	
							5950M	5410M			
DR	6410		5800			6350		5600	6240	6750	
F	6950					6840	6700				7445
CH	7390					7180		5860		7910	7990
HB	7550					7330				8010	8100
TS		2063		5600	2104						
TD	7660		6480			7400	7000	6010	8693	8180	8200

WELL NAME

	3104	3105	3301	3305	3306	3307	3308	3311	3312	3313	3314
REF. EL.	10	1	15	15	15	15	15	16	18	17	18
SYMBOL											
•				SOD				500	490		450
s				7Do				700	700		530
¥				830				810			660
P				940				950	940		930
ks				1520				1510	1520		1300
ne				1670				1670	1680		1660
PL			1850	1860	1850			1890	1900		1860
MI			3160	3170	3120			3390			
A						1800		3450			
a		3050		4250					4460		
	4980M										
AB	5ooo	5200	5330	4910	5100	4970	4760	5410	5760	5330	
	5980M										
SD						5600		6520	6950	6400	
DR	6480	6850	6900	6170	6430Pr	6160Pr	5730Pr	7200	7690	7060	
										7090F200	
F	7380	7730			7150						
CH		8160									
HB		8270					6540				
TD	7530		7011	6285	7501	6811	6788	7450	8141	7700	4744

Distribution:

U.S. DOE SPR Q (10)
900 Commerce Road East
New Orleans, LA 70123
Attn: J. C. Kilroy, PR-631
J. W. Kunkel, PR-622
D. W. Whittington, PR-622 (3)
L. J. Rousseau, PR-63
M. W. Smith, PR-641
TDCS **(2)**

U.S. Department of Energy (2)
Strategic Petroleum Reserve
1000 Independence Avenue SW
Washington, D.C. 20585
Attn: R. Smith
D. Johnson

Boeing Petroleum Services (6)
850 South Clearview Parkway
New Orleans, La 70123
Attn: T. Eyermann
J. McHenry
K. Mills
J. Siemers
J. Teerling
K. Wynn

Acres International Corporation (3)
140 John James Audubon Parkway
Amherst, NY 142281180
Attn: B. Lamb

Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303
Attn: Bhupen (Ben) Mehta

Louisiana Geological Survey(3)
University Station; Box G
Baton Rouge, LA 70893
Attn: C. G. Groat
W. J. Autin
Brigid Jensen

Solution Mining Research
Institute
812 Muriel Street
Woodstock, IL 60098
Attn: H. Fiedelman

Texas Bureau of Economic
Geology (3)
Univesity Station, Box X
Austin, TX 78713
Attn: W. L. Fisher
M.P.A. Jackson
S. J. Seni

Joseph D. Martinez
3641 S. Lakeshore Drive
Baton Rouge, LA 70808

T. R. Magorian (12)
133 South Drive
Amherst, NY 14226

L. S. Karably
Law Environmental, Inc.
223 Townpark Dr.
Kennesaw, GA 30144-5599

R. L. Thorns
AGM, Inc.
P.O. Box 10358
College Station, TX 77842

D. H. Kupfer
7324 Menlo Drive #3
Baton Rouge, LA 70808

A. H. Medley
1716 S. 75th E. Ave.
Tulsa, OK 74112

R. Ginn
Underground Injection Control
Railroad Comm. of Texas
Austin, TX 78711-2967

Injection and Mining Division
Louisiana Office of-conservation
P.O. Box 94275, Capitol Station
Baton Rouge, LA 70804-9275

Joe L. Ratigan
RE/SPEC, Inc.
3824 Jet Drive
Rapid City, SD 57709

Amoco Production Company (3)
Exploration Dept.
501 West Lake Park Blvd.
P.O. Box 3092
Houston, TX 77253
Attn: Allen Levine
William Hart
Jeff Spencer

Gregory K. Trahan
Hackberry Storage Facility
OXY USA, Inc.
101 Clarpha Rd.
Hackberry, LA 70645

Harry G. Allison
Golden Storage Services, Inc.
711 Louisiana, Suite 1600
Houston, TX 77002

Mr. Ben Knape
Texas Water Commission
1700 N. Congree Ave.
P.O. Box 13087 Capitol Station
Austin, TX 79811

Prof. Saul Aronow
Dept. Geology
Box 10031
Lamar Univesity Station
Beaumont, TX 77710

PB-KBB Inc. (2)
11767 Katy Freeway
P.O. Box 19672
Houston, TX 77224

Sandia Internal:

3141 S. A. Landenberger (5)
3141-1 C. L. Ward (8)
for DGE/OSTI
3151 G. C. Claycomb
for DOE/TIC
6000 D. L. Hartley
6225 H. J. Sutherland
6232 W. R. Wawersik
6232 D. H. Zeuch
6250 P. J. Hommert
6253 J. C. Lorenz
6253 D. S. Preece
6257 J. K. LiM (lo)
6257 B. Eghartner
6257 T. Hinkebein
6257 P. Kuhlman
6257 J. L. Todd
6257 J. T. Neal (15)
8524 R. C. Christman